Recent Progress in Direct Optical Imaging Technologies for Exoplanets

Marie Levine, JPL

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with contributions from

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Olivier	Guyon [3]
Jeremy	Kasdin [4]
Brian	Kern [2]
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Overview

- Intent is to provide snapshot of progress since last workshop :
  - Starlight Suppression Laboratory Demonstrations
  - Wavefront Sensing and Control
  - Coronagraph Optics
  - Modeling and Simulation
  - Facilities
- Present highlights only here. More details available
  - During mission presentations
  - Each technologists provided comprehensive charts (in backup)
- Vibrant community with significant progress since the last workshop
  - Mostly driven by the technology demonstrations for the ASMCS
  - Many collaborations
  - Many complementary activities
- Problems not solved yet to TRL 6
  - Most efforts at ~TRL 3-4 with proof of concept demonstrations
  - Need continued funding

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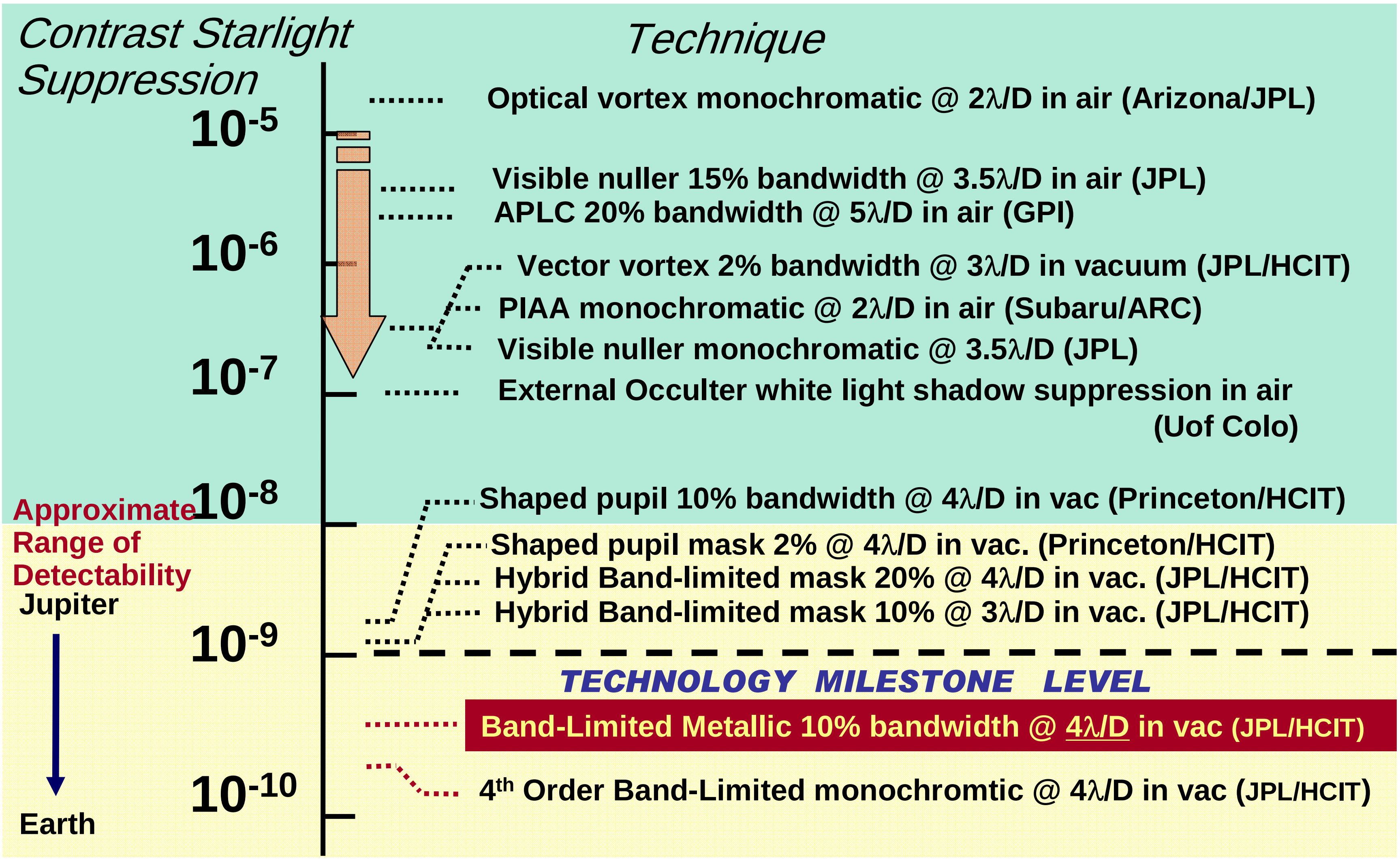
Starlight Suppression Status

ExoPlanet Exploration Program



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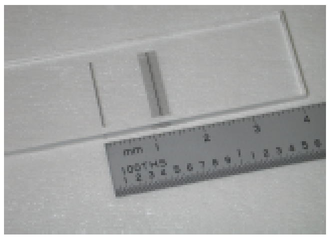
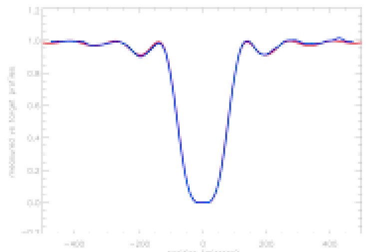
ASMCS ACCESS Demonstrations in HCIT
J. Trauger, JPL

Lyot coronagraph demonstrations on the HCIT



THICKNESS-PROFILED NICKEL MASK

Nickel mask has been vacuum-deposited on a fused silica substrate. Attenuation profile was built up in a number of passes with a computer-controlled moving slit. The same mechanism will be used to superimpose a dielectric phase layer in future work.



Comparison of the prescribed transmittance profile with the measured profile of the mask pictured at left. Desired profile is the red curve, the measured profile is the blue curve.

Recent contrast demonstrations in the HCIT:

IWA = 3 λ/D, 10% bandwidth, C = 1.2 e-9

IWA = 3 λ/D, 20% BW, C = 2.7 e-9

IWA = 4 λ/D, 10% BW, C = 6 e-10,

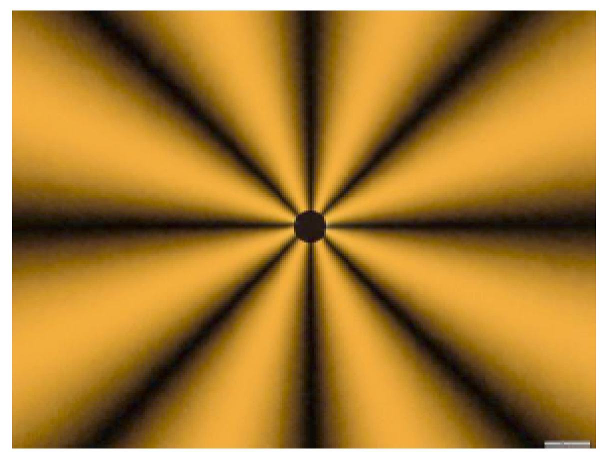
with 4th-order metallic or metal+dielectric 4th-order Lyot masks. All masks manufactured at JPL. Narrower (2.5 λ/D) Lyot masks, and circular masks will be manufactured this year.

Vector vortex coronagraph mask for HCIT experiments

Recent contrast demonstrations in the HCIT:

IWA = 3 λ/D, 2% bandwidth, C = 2.0 e-7

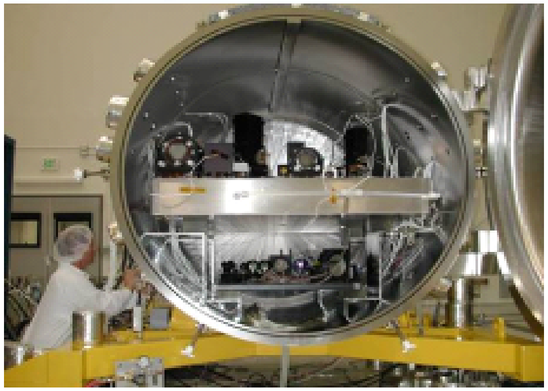
with the first-ever charge-4 liquid crystal polymer vortex mask from JDSU (seen at left through crossed polarizers). Close agreement between HCIT performance and models predict that reduction of internal reflections and multilayer achromatization will lead to contrast ~1e-9 with a 20% bandwidth, to be attempted by the end of this year.



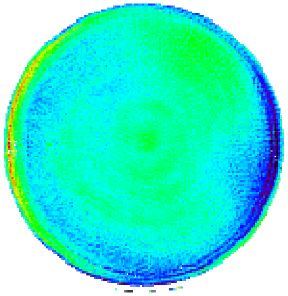
ASMCS PECO & ACCESS: PIAA Demonstrations

O. Guyon U of A, J. Trauger JPL, B. Kern JPL, R. Belikov ARC

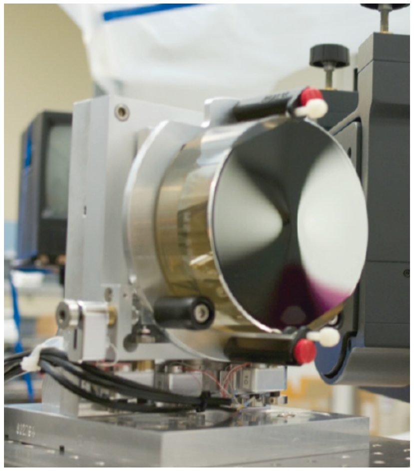
- **PIAA-2 mirrors fabricated by Tinsley (under contract to NASA Ames) have been installed into optical train and placed in HCIT vacuum tank**
- **PIAA-2 mirrors were aligned to each other using Zygo**
  - Some surface errors not seen in CGH maps (Not due to alignment of PIAA mirrors)
- **HCIT testing in progress with PIAA-2 optics**
  - Will demonstrate $<10^{-9}$ contrast in 5%, 10%, 20% bandpasses
  - Dark hole expected to extend as close as $2.3\ \lambda/D$ from star
  - Model validation will refine mirror requirements for possible "gen-3" optics
- **To date PIAA system validated at ~10^{-7} contrast (monochromatic) at 1.67 λ/D in air**
  - Subaru Telescope testbed with MEMs DMs & PIAA-1 (co-funded by Subaru & NASA JPL) & new NASA ARC test facility w/ lenses
  - Inverse PIAA corrective optics demonstrated
  - Refractive PIAA system built for Subaru Telescope: first light 2010
- **Pointing sensing & correction with Low Order Wavefront Sensor demonstrated to 0.1mas requirements for 10^{-10} contrast (Subaru Telescope testbed)**
  - Validates the PIAA system architecture
  - Plans to incorporate LOWFS into HCIT PIAA-2 system (summer '09)



PIAA-2 in HCIT



PIAA-2 M1 & M2 double-pass alignment residuals, Zygo at M1



PIAA-2 mirror from NASA ARC/ Tinsley

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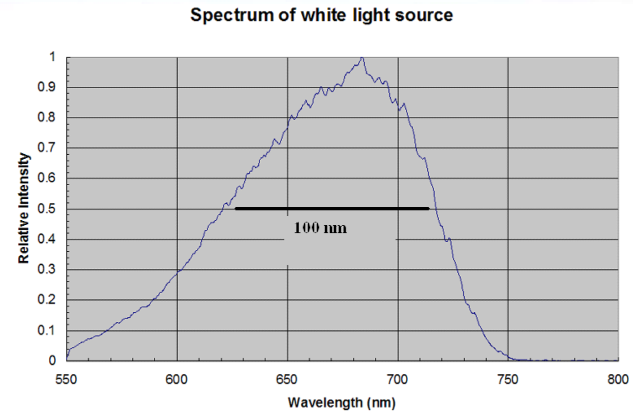
ASMCS EPIC & DAVINCI: Visible Nuller Demonstrations

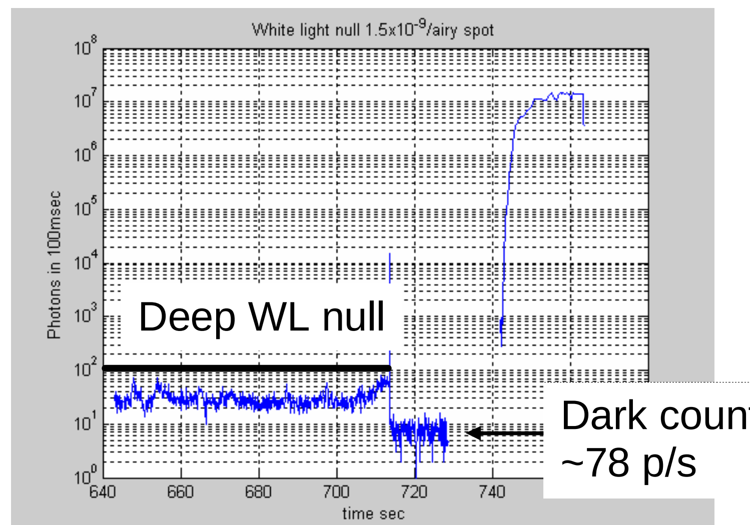
M. Shao JPL, M. Clampin GSFC, B. M. Levine JPL, R. Lyon GSFC

ExoPlanet Exploration Program

- **VNC testbed at JPL**
  Single fiber null achieves 10^{-6} starlight suppression in 15% band. (10^{-9} /airy spot)
  - Sufficient for EPIC
  - Results for laser light are 10 lower as required for DAViNCI
- **GSFC VNC testbed**:
  - Nulling interferometer demonstrates closed loop control of nulling algorithm
  - Expects to achieve ~10^{-9} contrast > 5% band.
- **Future demonstrations:**
  - Incorporate complexity of coherent fiber bundle with lenslet array
  - Perform demonstration over relevant time scales
  - multi-pixel high contrast imaging



15% white light source after propagation through one arm of the interferometer. The Full width at half maximum is 100 nm.

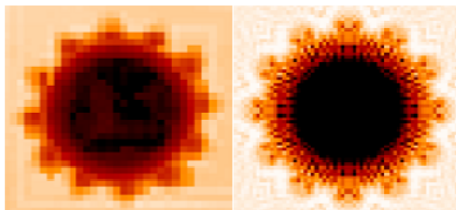


Samuele et. al. (2007) IEEE #1366

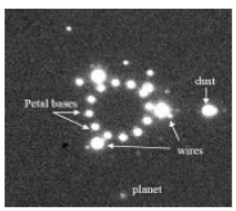
ASMCS NWO & THEIA: External Occulter Demonstrations
A. Lo NGST, W. Cash U of Co, J. Kasdin Princeton U

Colorado Testbed

12 petal NIST subscale starshade
Experiment located at NCAR's coronagraphic testing facility



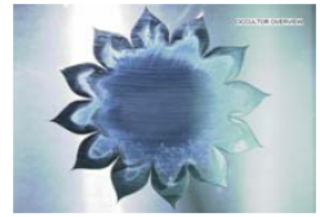
Right: PMT measurement of shadow, Left: simulation

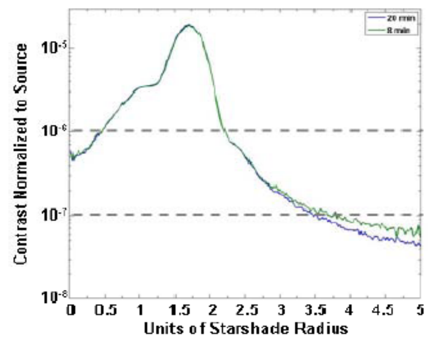


Artifacts due to experiment set up is limiting our suppression measurement
Bright spots are at 2 x10^{-7}
Suppression at 10^{-8}
Off-axis source seen at 10^{-9}

Northrop Testbed

12 petal NG subscale starshade
Experiment located at Northrop Grumman, Space Park



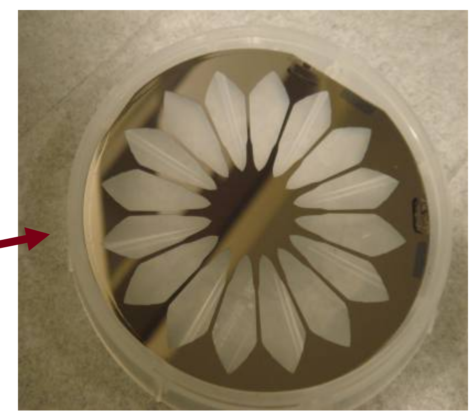


Suppressions below 10^{-7} are being recorded

We are currently improving the testbed noise floor

A false peak due to the experimental set up is limiting the contrast measurement.

- **Princeton Testbed**
  - 2-year verification study to examine occulter performance at 10^{-8} to 10^{-10} level
  - Uses a diverging beam from a spatial filter to minimize aberrations from optics
  - Uses an optimized outer structure on a free-standing mask w/ appropriate Fresnel number – delivered by JPL
  - Currently under construction, first results expected by summer



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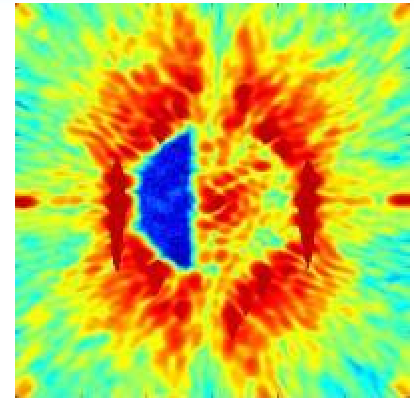
Wavefront Control Algorithms

A. Give'on JPL, L. Pueyo Princeton/JPL, J. Kasdin Princeton

ExoPlanet Exploration Program

Electric Field Conjugation Sensing & Control (A. Give'on JPL): Becomes the standard for internal coronagraph WFSC Testing

Image plane sensing, DM diversity-based wavefront reconstruction + **Electric Field Conjugation Correction** =



Performance
- Reaching better contrasts and in far fewer iterations than any previous methods

Cross-systems
- Testbeds (HCIT, Princeton, Santa Cruz)
- Coronagraphs (band limited, Shaped pupils, optical vortex, APLC, PIAA)

Modular
- Broadband correction, 1 and 2 DM's, Different dark hole regions,

Robust
- Can accommodate errors and changes in the system (such as bad actuators)

Results

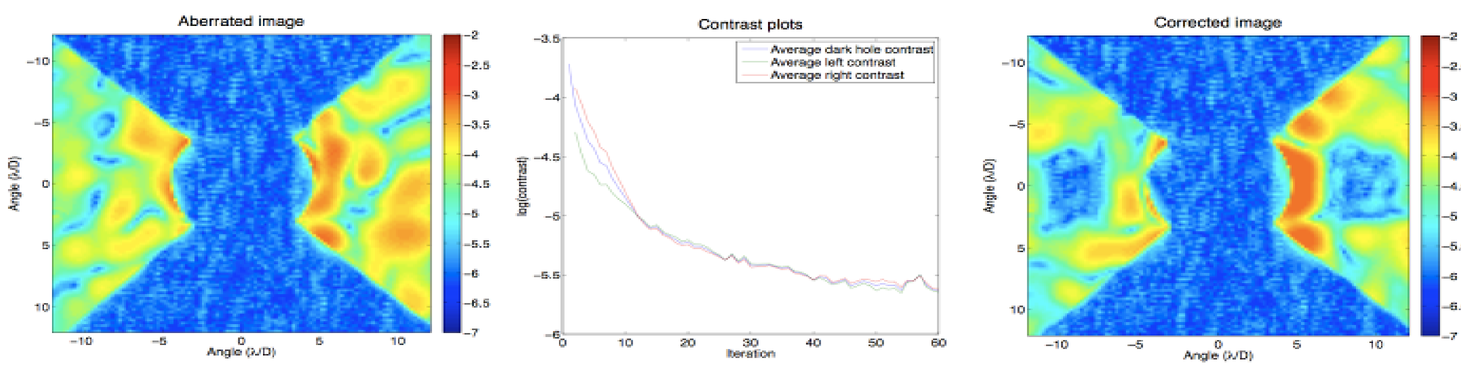
BLC: 6e-10, @ 4 λ/D with 10% light
1.2e-9, @ 3 λ/D with 10% light
2.7e-9, @ 3 λ/D with 20% light

SPC: 1.16e-9, @ 4 λ/D with 2% light
2.4e-9, @ 4 λ/D with 10% light

OVC: 2e-7, @ 3 λ/d with 2% light

Symmetric Dark Holes Using <u>2-DM</u> Stroke Minimization w/ a Pairwise Estimator (Princeton)

- Electric field conjugation estimators using DM diversity in the image plane for amplitude & phase correction
- Development of non-deterministic estimators using control theory filtering techniques

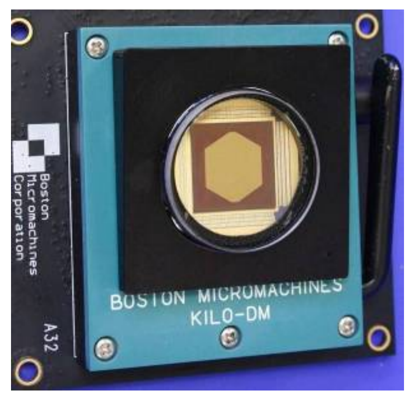


Deformable Mirrors

J. Trauger , M. Shao, B. Levine JPL, M. Clampin GSFC, R. Belikov ARC w/ USCS

- **Xinetics**
  - 32x32 currently in use in HCIT / JPL
  - 64x64 to be installed summer '09
  - 48x48 proven to TRL6 by end of '09
  - Fuse Silica facesheet polished to $\lambda/100$ rms
  - Surface stable to 0.01 nm rms over > 6 hours in vacuum
- **Boston Micromachine**
  - Under investigation for PECO, EPIC and DAViNCI
  - TPF-C contract-69 segment proof of concept
  - JPL SBIR Φ1& 2- 331 segment device
  - 1027 segment device required
- **IRIS-AO**
  - GSFC Phase 1-2 SBIR 992 segment demonstrator
  - GSFC Phase 1 electrically connected segmented DM (331 segments)
  - 1027 segment electrically connected req'd

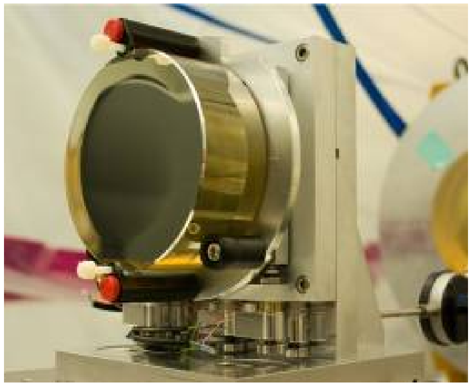
Boston Micromachine



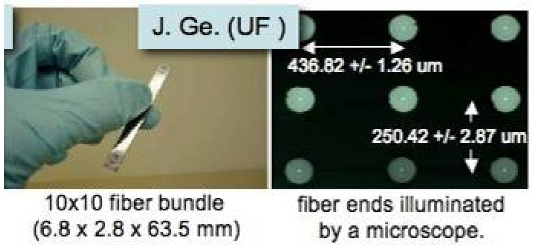
Precision Optics

ExoPlanet Exploration Program

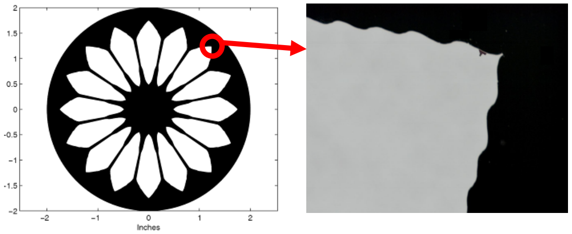
- **PIAA Aspheric Optic (ASMCS PECO & ACCESS)**
  - Generation 1 (funded by NASA JPL, manufactured by Axsys) delivered 2006: Diamond turned Al(25 nm RMS system WFE)
  - Generation 2 (funded by NASA Ames, manufactured by Tinsley) delivered Jan’09: Zerodur (10 nm RMS system WFE (filtered to 20 CPA))
- **Single Mode Fiber & Lenslet Arrays (EPIC & DAViNCI**
  - Existing demonstration units (< 2007)
    - 331 fibers w/o array
    - 100 fibers with partial array integration (U of Florida)
  - Fiberguide Industries to deliver units by 2009
    - 217 fibers integrated with custom lens array
    - To be used in APEP & GSFC testbeds
  - Future development Need: 1027 fibers fully integrated
- **Coronagraphic Masks & Stops (ACCESS)**
  - Development of new dielectric Lyot masks and Optical vector vortex masks (ASMCS ACCESS)
- **Free Standing reduced scale external occulter (ASMCS THEIA)**



PIAA-2 mirror from NASA ARC/ Tinsley



Single Mode Fiber Array (U of FL)
Single Mode Fiber Array (U of FL)



Free Standing External Occulting Mask (JPL)

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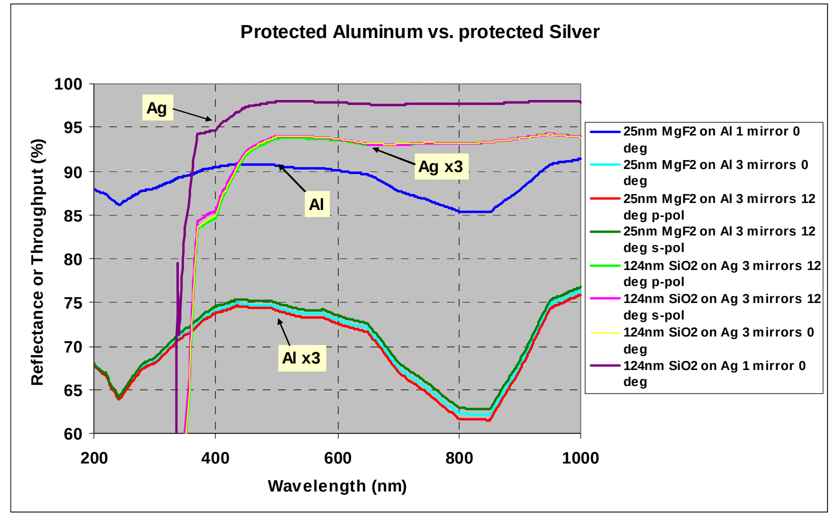
Coatings, Polarization & Contamination

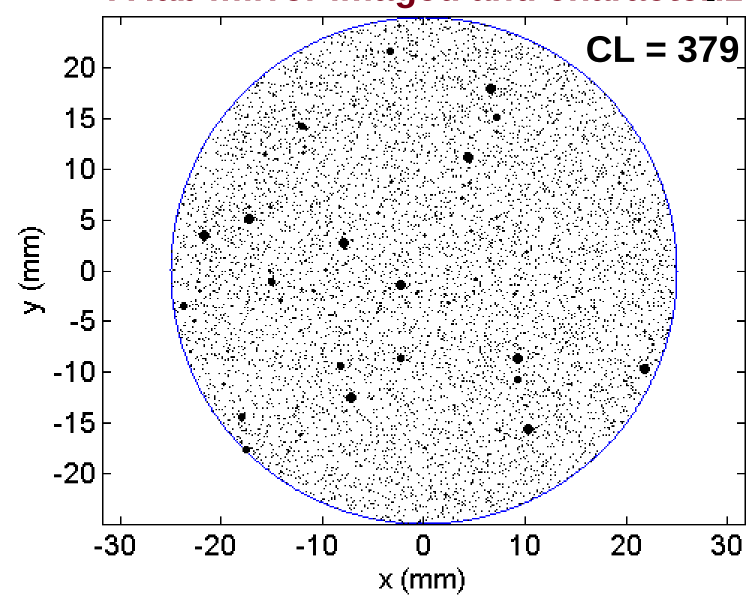
K. Balasubramanian, JPL

ExoPlanet Exploration Program

- Activity started in FY'09
- Optical starlight suppression models to date do not address:
  - Coating & uniformity
  - Polarization
  - Contamination
- Performance impact:
  - DM's compensate for the coherent part of scattered light; work in progress
  - An OAP from HCIT was characterized to be at CL 300; yet, we achieved a contrast of 5×10^{-10} with DM controls
  - Coatings also affect throughput, reflectivity, spectral bandwidth



A lab mirror imaged and characterized



Particle sizes exaggerated for visualization

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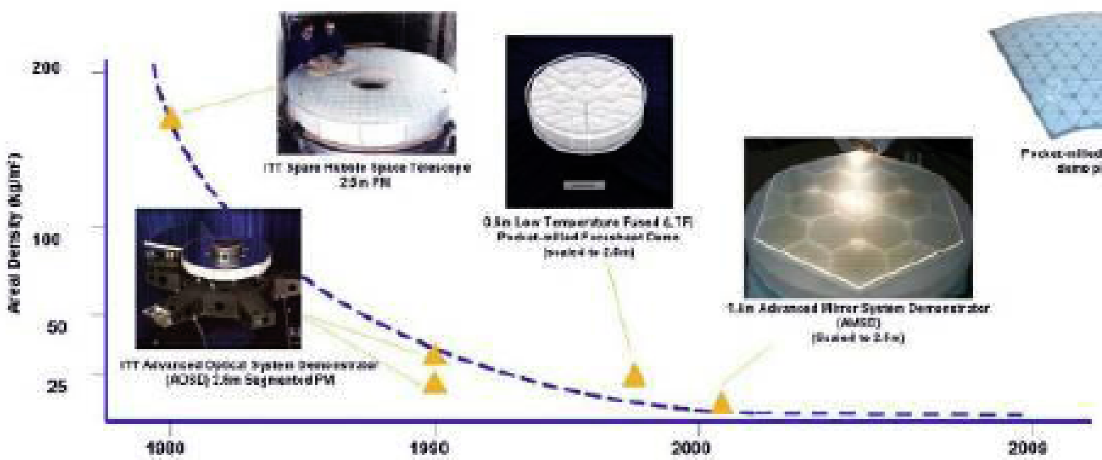
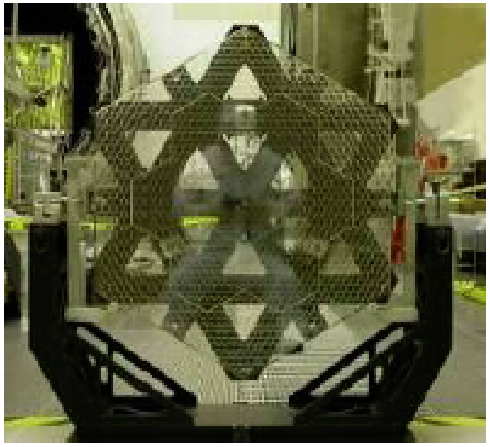
Primary Mirror SOA Technology

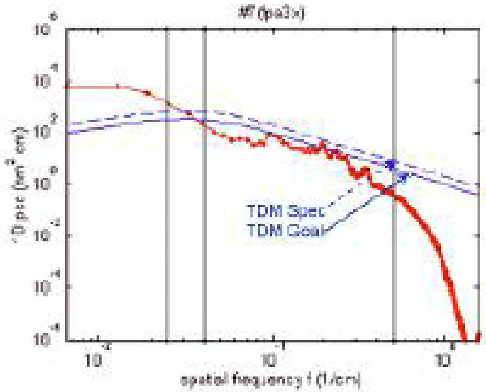
R. Egerman, ITT Space Systems LLC



PM Areal Density, cost, risk and schedule
has been reduced dramatically without sacrificing performance



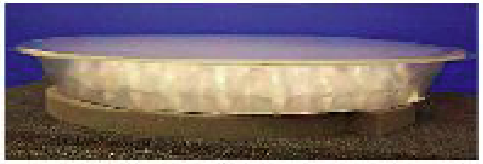
ITT has matured its AMSD
ultra-lightweight active mirror
bringing it to TRL 6 and demonstrating a
reflected WFE of <25 nm-rms



ITT has demonstrated finishing to coronagraphic requirements on 1-2m class on-axis mirrors, off-axis optics in this class do not pose significant challenges

3 layer micro-corrugation facesheet

Layer 4 Macro Corrugation



Finished plano 0.6m mirror blank

ITT has finished a plano 0.6m Corrugated Borosilicate mirror to 380 nm-rms. After one ion figuring run, the error is expected to drop to ~75 nm-rms, and ultimately to ~20nm-rms

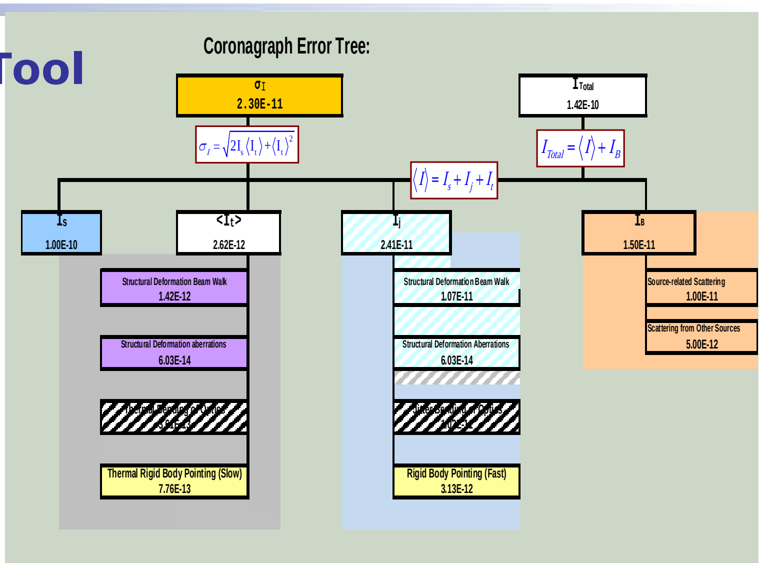
ITT

Modeling & Simulation (1/3)

Generalized Coronagraph Error Budget Tool

L. Marchen & S. Shaklan, JPL

- Automated error budget tool for most coronagraph systems: observatory tolerances to back-end contrast
- Based on optical sensitivities analyses of actual optical prescriptions and diffraction analyses of the specific coronagraph (Lyot, PIAA, Vortex)
- Status: end-to-end Analysis code validation complete. Automation in progress.

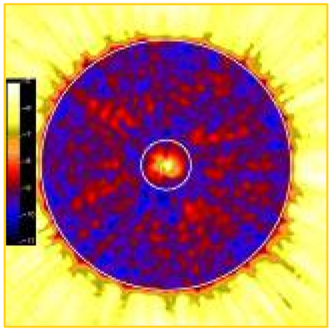


Coronagraph Error Budget Tool Screenshot

PIAA Modeling

O. Guyon UofA, J. Krist, L. Pueyo, E. Sidick, S. Shaklan, JPL, R. Belikov NASA Ames

- HCIT PIAA Models & Error Budget Verification
  - Study the sensitivity of broad-band contrast to alignment, motion, bending, and other perturbations
  - Combine a diffraction model of PIAA with a MACOS model of the testbed, and apply the latest EFC algorithm for WFS/C using single and dual DMs.
- End-to-end modeling of PIAA coronagraph with realistic optics and wavefront control
  - Investigate ability to create high contrast fields over broad passband
  - Establish optical surface requirements



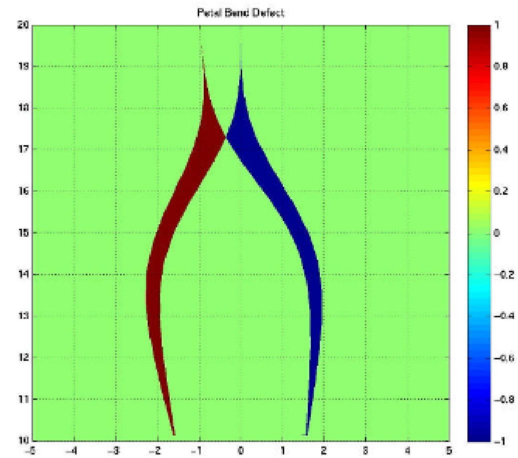
PIAA Achieves 8x 10^{-10} with 0.25nm RMS on post-PIAA OAPs and 1.25nm RMS on other non-PM optics

External Occulter Modeling

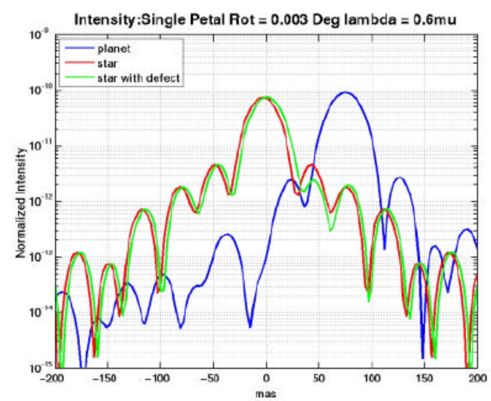
P. Dumont, S. Shaklan JPL, J. Kasdin Princeton, R. Lyon GSFC, NGST/CU

- Large scale optical diffraction models to simulate the effect of petal deformations and defects on broadband contrast
  - Stand-alone and hybrid coronagraph/occulter systems
  - Used for developing occulter tolerances
  - Will be linked to thermo-structural-dynamic code for transient contrast simulations

- Several approaches are being considered:
  - Computational efficiency is critical for evaluating mm tolerances on 10's m class structures
  - JPL: Combine analytic solution for the occulter field at the telescope with a near-field diffraction model at the optical system using Babinet's principle
  - GSFC: Brute force Fresnel propagation w/ big FFTs. Also implemented Bessel function and edge line integral propagators
  - Separate activities at NGST/ Caltech
  - Results can be cross-checked for verification



Occulter petal in-plane bending

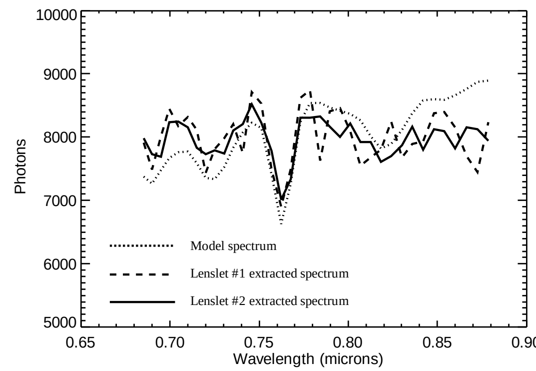


Intensity vs IWA due to ~3milli geg rotation of single petal (20 petals, 40m tip-tip occulter)

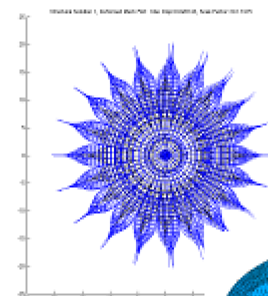
Other Modeling & Simulation

ExoPlanet Exploration Program

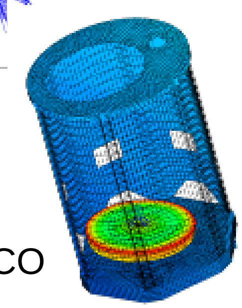
- **Visible Nuller** R. Lyon, GSFC
  - Comprehensive end-to-end model of VNC completed as part of EPIC ASMC
  - includes all surfaces, raytrace, diffraction, polarization, dispersion, fibers and detectors, etc...
- **Extraction of Planet Spectra** J. Krist, JPL
  - End-to-end model of Lyot coronagraph w/ aberrations WFC
  - Chromaticity of speckles determined
  - Planet spectra extracted via roll subtraction, spectral filtering
- **Integrated Modeling** G. Moore et al., JPL
  - Analysis of multi-physics integrated models (thermal, structures, optics, controls, jitter):
  - Handles very large problems and transient simulations: Thermal ⟶ Contrast
  - Enable closed-loop, system-level analysis and design, correlation and optimization



Extracted Earth spectrum from a simulated Coronagraphic dark field.



THEIA

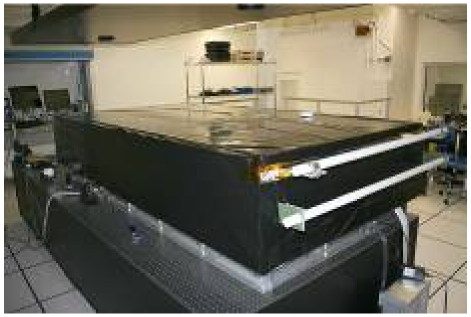


PECO

Recent Facilities

- **High Contrast Imaging Testbed (HCIT) JPL**
  - Premier facility for vacuum testing of coronagraph concepts
  - FY’09 upgrade: 2nd bench added this year for efficient testing of multiple approaches
  - Completed testing of ACCESS Dielectric BL masks and Vector Vortex masks
  - PIAA testing in progress for ACCESS and PECO
- **NASA Ames PIAA Coronagraph Facility**
  - New testbed dedicated to PIAA testing in air
  - Will explore PIAA architectures w/ multiple channels
  - Will study the feasibility of MEMs DMs
  - To date achieved 4 x 10^{-7} in air and monochromatic
- **Visible Nuller Testbeds**
  - GSFC: demonstrating null control algorithms in air
  - APEP/ JPL: Vacuum demonstration of broadband visible nulling system through fiber bundle
    - Will provide: 16-bit DM electronics, coherent fiber bundle and Lens array, and control system

HCIT w/ PIAA Installed



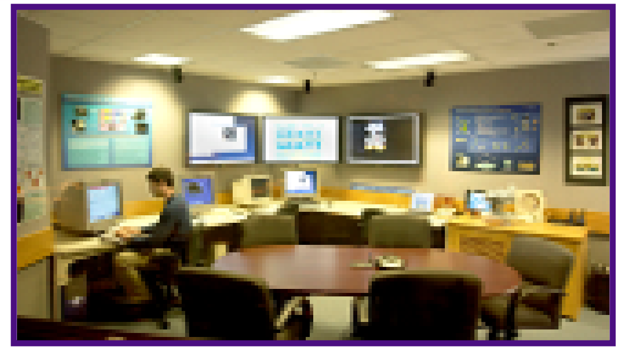
Ames PIAA Testbed

Coherent Fiber Bundle

Formation Flying Technology Laboratory

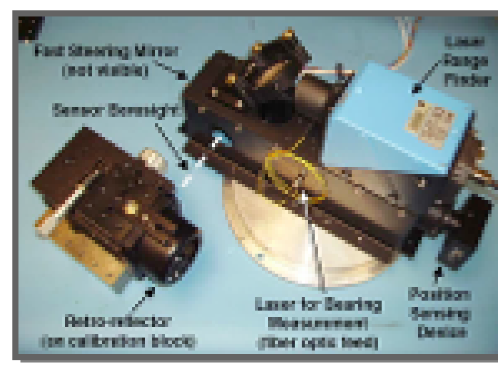
D. Scharf, JPL

- *Example External Occulter application:* Demonstration of Precision Bearing Control with Attitude and Bearing Sensor Misalignments
  - Pointing telescope + occulter while maintaining lateral alignment *couples formation attitude and formation translation control*
  - Autonomous acquisition of fine bearing sensor and calibration of misalignments at varying sun angles (varying thermal environment) key
    - 1 m lateral alignment at 30,000 k is ~30 nrad req.
  - Demonstrate acquisition/calibration with multi-level sensing in FCT
  - Demonstrate integrated formation pointing and alignment capability



Formation Flying Technology Lab Operations Room

Formation Control Testbed w/ 2 Robots

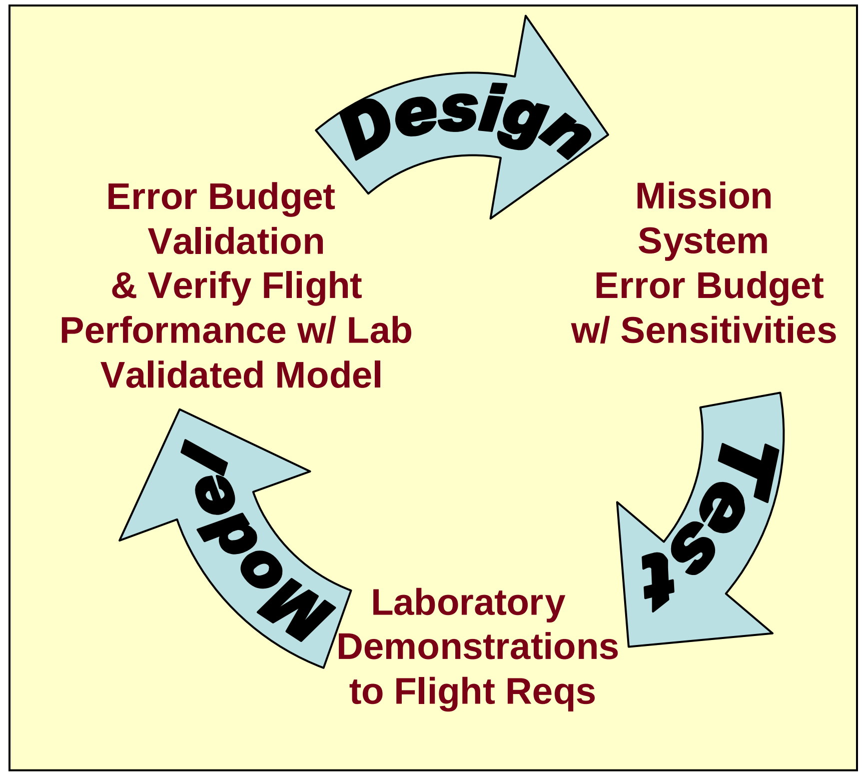


Inter-Robot Bearing Sensor

Technology Milestones

- Need standardized / systematic approach to mature technologies to TRL 6 and to measure progress towards flight
  - Most on-going activities focused on proof of concept demonstration to show that physics are understood (~TRL 3-4)
- Each step/Milestone links the technologies to flight design
  - Complexity
  - Timescale
  - Relevant environment
- Formal 3-step process ties:
  - Flight requirements
  - Lab demonstrations
  - Validations of error budgets & models
- Requires formal peer review
- TPF-C Milestone Reports:

http://planetquest/TPF-C/TPFC_M1_Report_060710_final.pdf
http://planetquest/TPF-C/HCIT-Milestone2Signed-2008-08-08.pdf



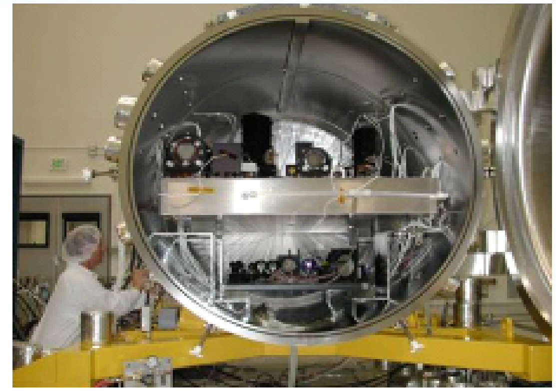
Additional Information

Starlight Suppression Laboratory Demonstrations

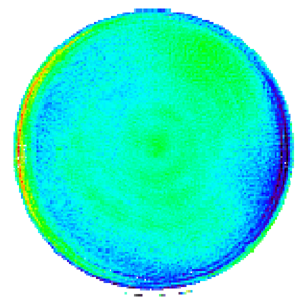
ASMCS PIAA Demos in HCIT (PECO & ACCESS)

B. Kern, JPL

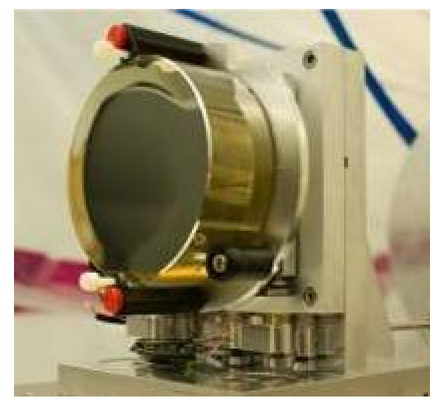
- PIAA coronagraph creates PSF w/deep contrast by optically rearranging pupil brightness
  - Very little absorption implies high throughput
- Wavefront control accuracy determines environmental stability criteria
- PIAA mirrors fabricated by Tinsley (under contract to NASA Ames) have been installed into optical train and placed in HCIT vacuum tank
- PIAA mirrors were aligned to each other using Zygo
  - Some surface errors not seen in CGH maps (Not due to alignment of PIAA mirrors)
- Attempt to demonstrate 10^{-9} contrast in 5%, 10%, 20% fractional bandpasses
  - Dark hole expected to extend as close as $2.3\ \lambda/D$ from star



PIAA in HCIT



PIAA M1 & M2 double-pass alignment residuals, Zygo at M1



PIAA-2 M1 mirror from NASA ARC/ Tinsley

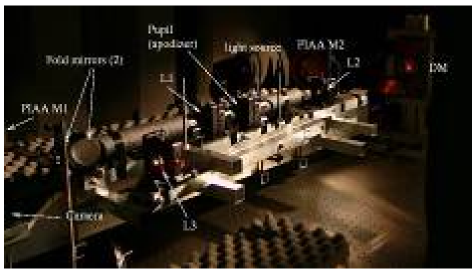
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

PIAA coronagraph system

O. Guyon, Univ of Arizona

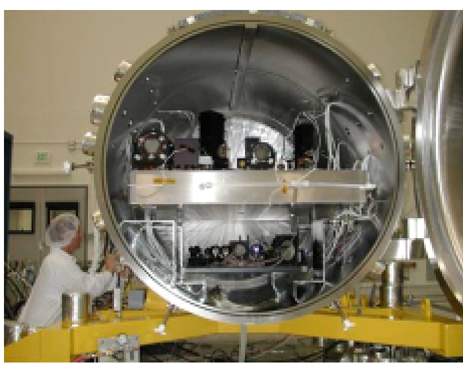
- “Hybrid” PIAA + apodizer approach allows the design to be tuned to meet aspheric mirror manufacturing capabilities with little loss in performance Low order wavefront sensor (LOWFS) uses starlight blocked by the coronagraph focal plane mask to meet tight tip-tilt control requirements of a low IWA PIAA coronagraph
- Inverse PIAA optics allow wide high contrast field of view with no image distortion

Laboratory demonstration (NASA Ames, NASA JPL & Subaru)

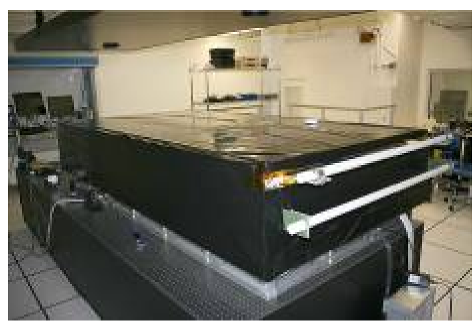


PIAA system validated at ~1e7 contrast level (monochromatic) within 2 l/D in air at testbed in Subaru Telescope (co-funded by Subaru & NASA JPL)

- sensing & correction of pointing demonstrated to requirements for 1e-10 contrast (1e-3 lambda/D) with Low Order Wavefront Sensor
- PIAA “hybrid” architecture validated
- Inverse PIAA corrective optics demonstrated in lab
- refractive PIAA system built for Subaru Telescope: first light in early 2010



PIAA tests are starting in High Contrast Imaging Testbed (HCIT) with new high quality reflective PIAA optics.



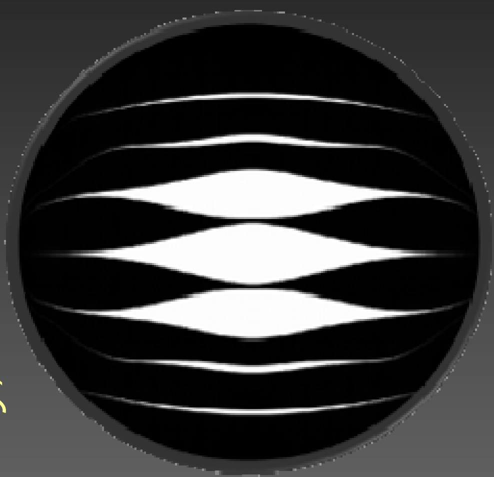
New PIAA testbed at NASA Ames aimed at exploring PIAA system architecture in a flexible stabilized non-vacuum enclosure

Testbed includes lessons learned from Subaru Testbed

Starlight Suppression Projects at Princeton HCIL

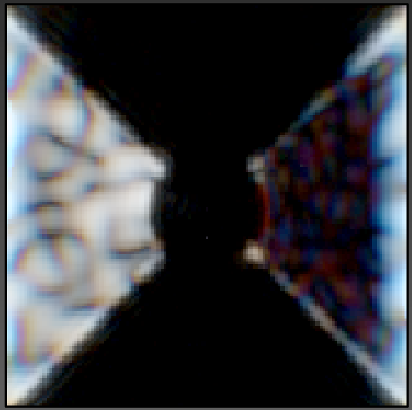
R. Belikov, Princeton/NASA Ames

High-Contrast Imaging Laboratory, Princeton University



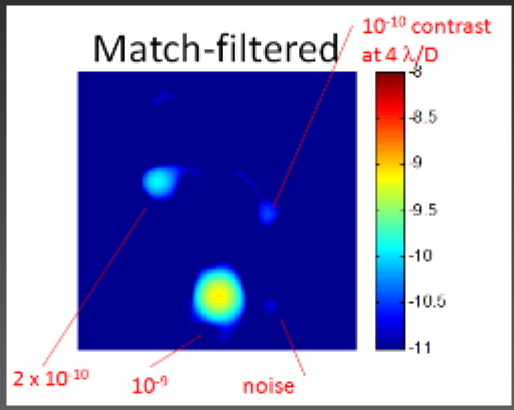
shaped pupil

Lab image (HCIT)

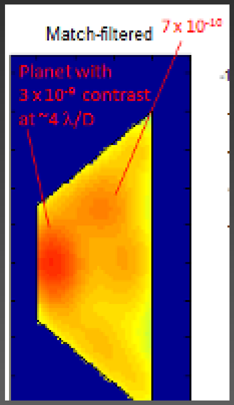


2.4 x 10^{-9} from 4-10 λ/D
in a 10% band
(former world record)

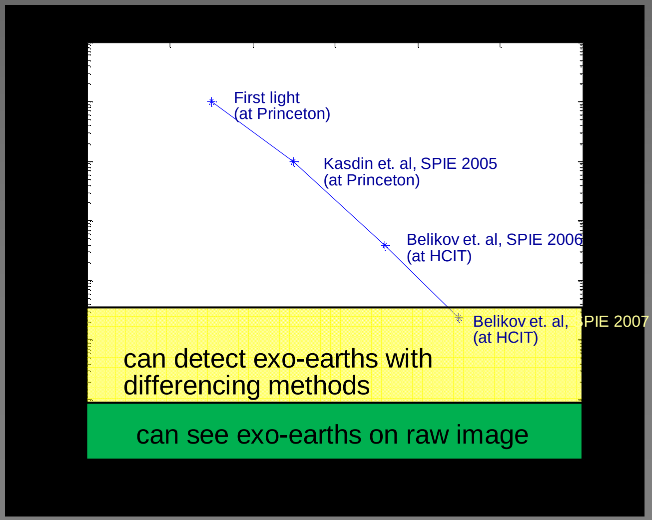
ADI+matched filer



CDI+matched filer



Synthetic planets recovered from lab images, including one at 4 λ/D with contrast 10^{10}



- Very successful project, collaboration between Princeton, JPL, and others
- Shaped pupils are simple, cheap, low risk, high marurity
- However, performance is lower than the highest-performing coronagraphs
- Lab demonstration: 2.4 x 10^{-9} speckle contrast at 4 λ/D in 10% BW
- 6.7 x 10^{-11} with ADI and 2.6 x 10^{-10} with CDI (post-processing techniques)
- With this level of performance in space, it may be possible to already image the neareast exo-Earths with a ~4m telescope

Starlight Suppression Projects at Princeton HCIL

J. Kasdin, Princeton

<u>Coronaphs</u>

- Optimization of hybrid coronagraphs using pupil mappers, shaped pupils, and DM’s
- Solving the pupil mapping problem for square geometry to use two DM’s pupil mappers

<u>External Occulter</u>

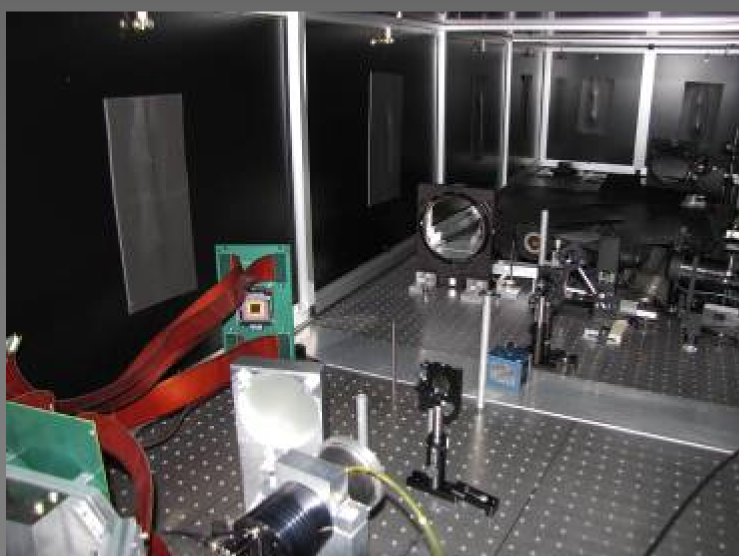
- Design and experimental verification of scaled occulter/telescope configurations
- Control system design of formation flying for a telescope and occulter

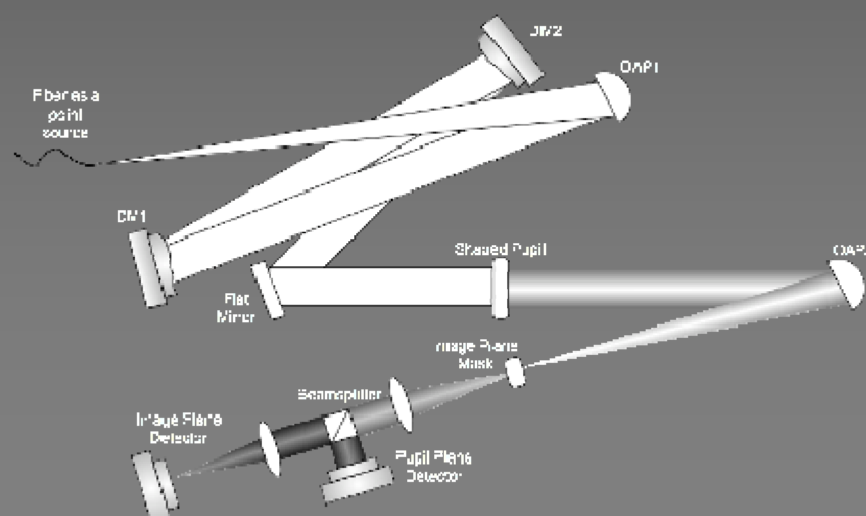
<u>Electric Field Estimation</u>

- Pairwise estimators using DM diversity in the image plane
- Development of non-deterministic estimators using control theory filtering techniques

<u>Wavefront Control</u>

- Two DM’s in series for Symmetric dark-zones and >10% $\Delta\lambda/\lambda_0$ broadband control





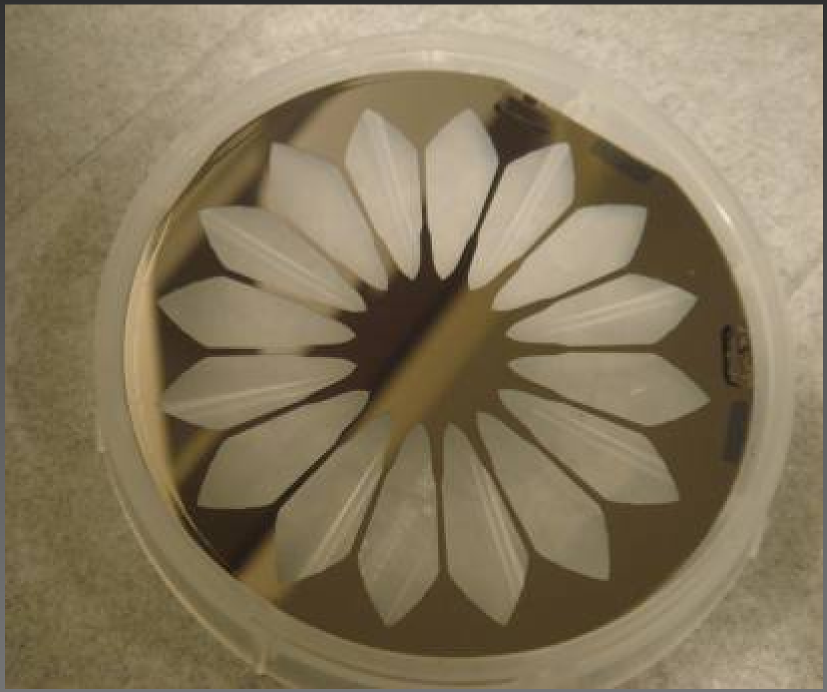
Occulters at Princeton
J. Kasdin

Experiment:

2-year verification study to examine occulter and hybrid occulter performance at 10^8 to 10^{10} level

- Uses a diverging beam from a spatial filter to minimize aberrations from optics
- Uses an optimized outer structure on a free-standing mask

Currently under construction, first results expected by summer



Other occulter work:

Design theory (perturbation analysis and tolerancing, occulter shape modification)

Sensing and control (closed loop fine guidance sensing in H-band)

Wavefront Sensing and Control

Symmetric Dark Holes Using 2-DM Stroke Minimization with a Pairwise Estimator

J. Kasdin, Princeton

Cost Function:

$$J = X\left(Id + \mu\left(\frac{2\pi}{\lambda}\right)^2 M\right)X^{\mathrm{T}} + 2\mu\frac{2\pi}{\lambda}X\Re(b^{\mathrm{T}}) + \mu\left(d - 10^{-C}\right)$$

$$X = [a_{1,1}, a_{1,2}, \ldots, a_{N,N-1}, a_{N,N}]$$

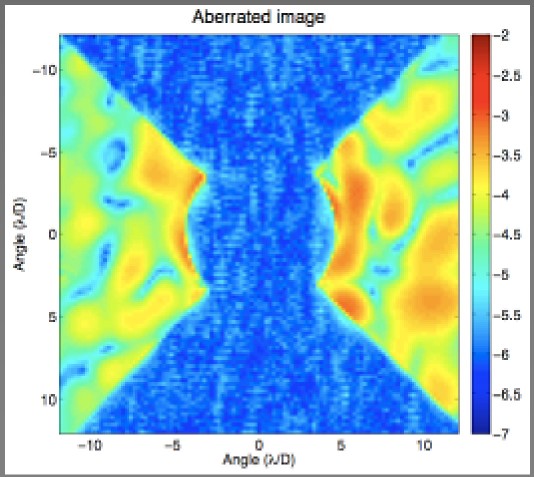
•Vector of Actuator Strengths

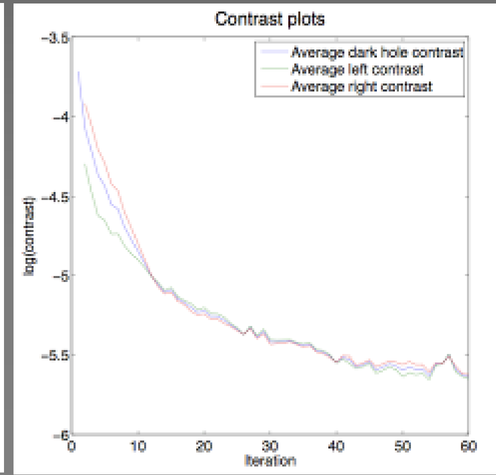
$$\begin{aligned} M_{k,l} &= \langle \mathcal{F}\{Af_{p(k),q(k)}\}, \mathcal{F}\{Af_{p(l),q(l)}\}\rangle \\ b_k &= \langle \mathcal{F}\{Af_{p(k),q(k)}\}, \mathcal{F}\{A\} + \mathcal{F}\{Ag\}\rangle \\ d &= \langle \mathcal{F}\{Ag\}, \mathcal{F}\{Ag\}\rangle \end{aligned}$$

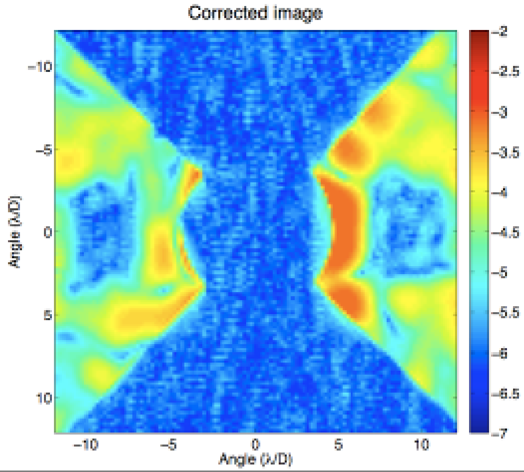
•Dark-Zone effect of each DM basis function

•Dark-Zone effect of basis function w/ aberrations

•Dark-Zone Effect of Aberrations

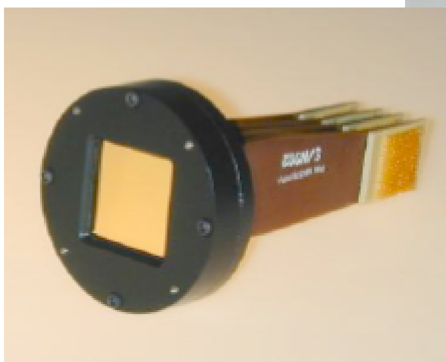


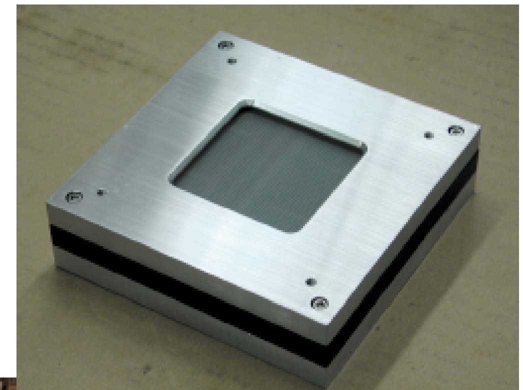


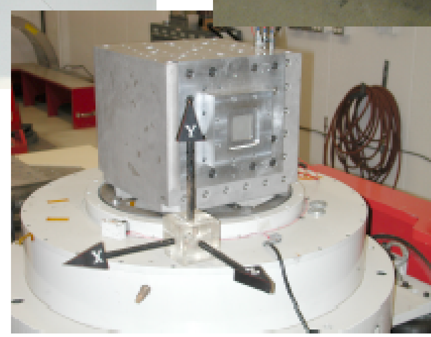


Xinetics Precision Deformable Mirrors

J. Trauger, JPL







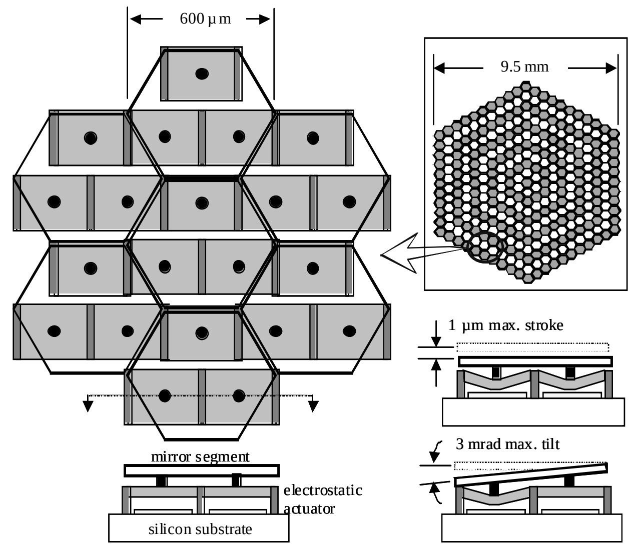
Evolution of monolithic PMN deformable mirrors: left to right: 32x32 array, used for all HCIT milestones to date; 64x64 array to be installed on HCIT spring 2009; 48x48 array (also shown on JPL shake table) will be used to demonstrate TRL6 flight-readiness this year.

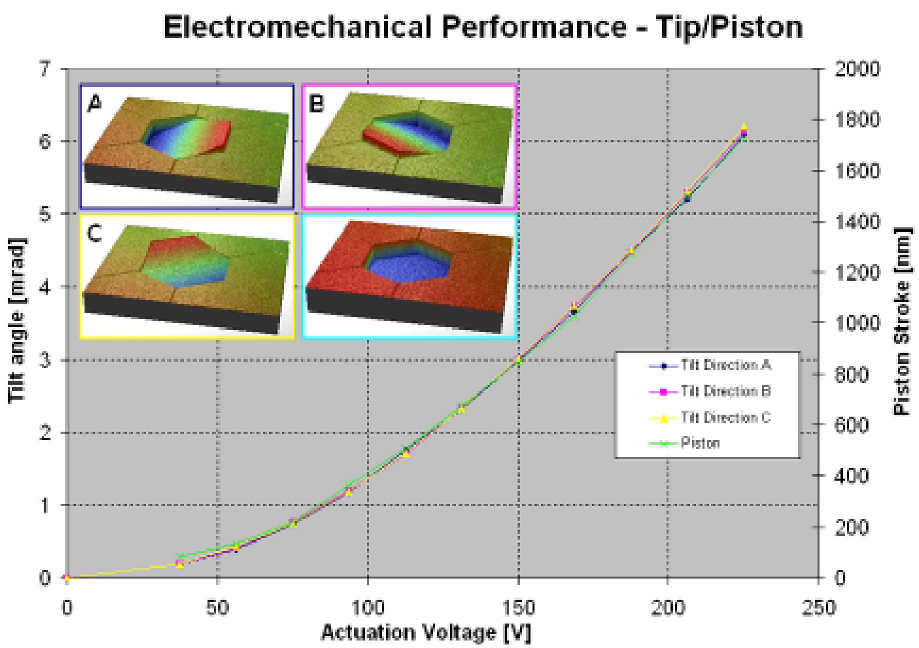
Mirror facesheets are fused silica, with surfaces polished nominally to λ/100 rms. Surface figure (open loop) is settable and stable to 0.01 nm rms over periods of 6 hours or more in a vacuum testbed environment. All DMs were delivered to JPL by Xinetics.

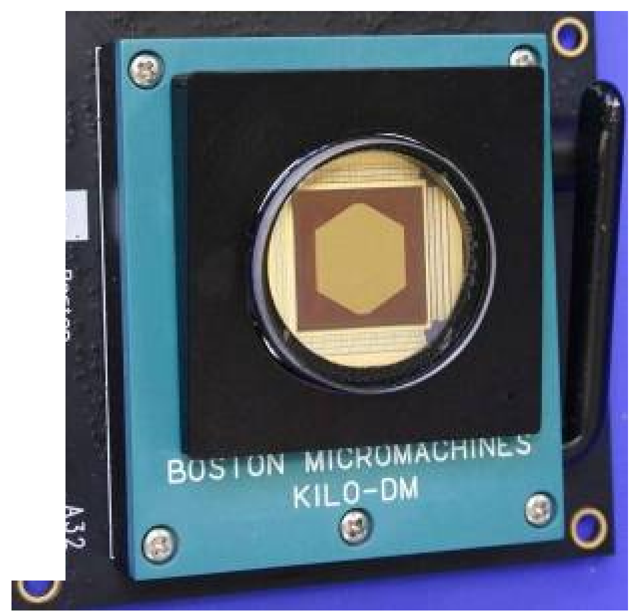
Boston Micromachines DM

B. M. Levine & M. Shao, JPL

- **Development history**
  - TPF-C contract-69 segment proof of concept
  - SBIR phase 1 and 2-331 segment device
- **Future development**
  - 1027 segment device required





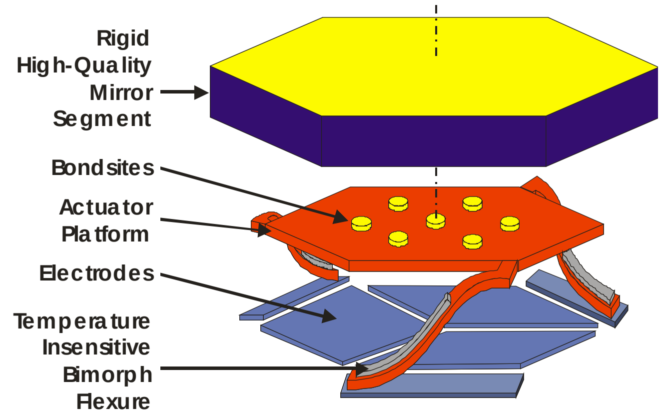


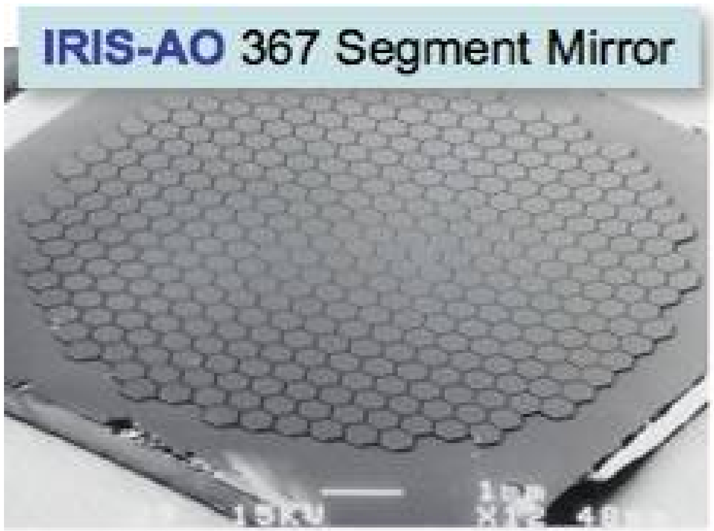
Iris AO DM

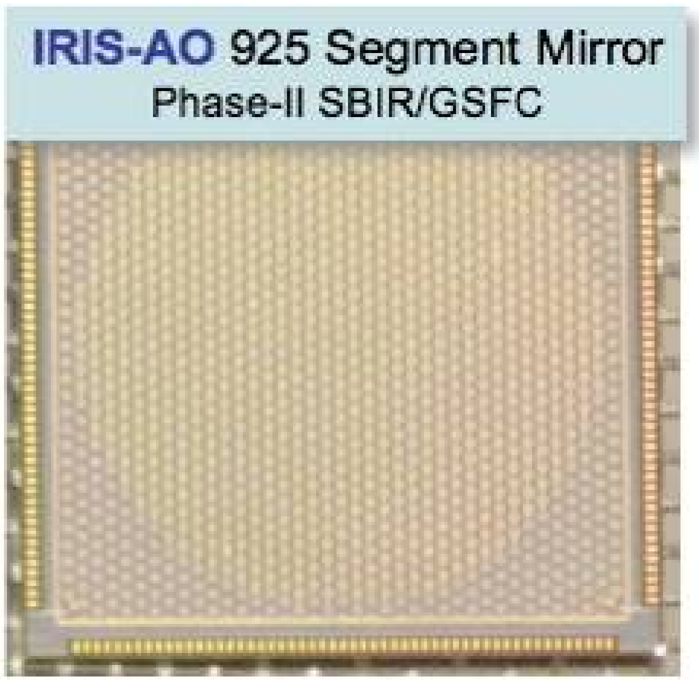
B.M. Levine & M. Shao, JPL

ExoPlanet Exploration Program

- **Development History**
  - Phase 1 and 2 SBIR 992 segment demonstrator
  - Phase 1 electrically connected segmented DM (331 segments)
- **Future development**
  - 1027 segment electrically connected







DM Requirements for Visible Nullers

B. M. Levine, JPL

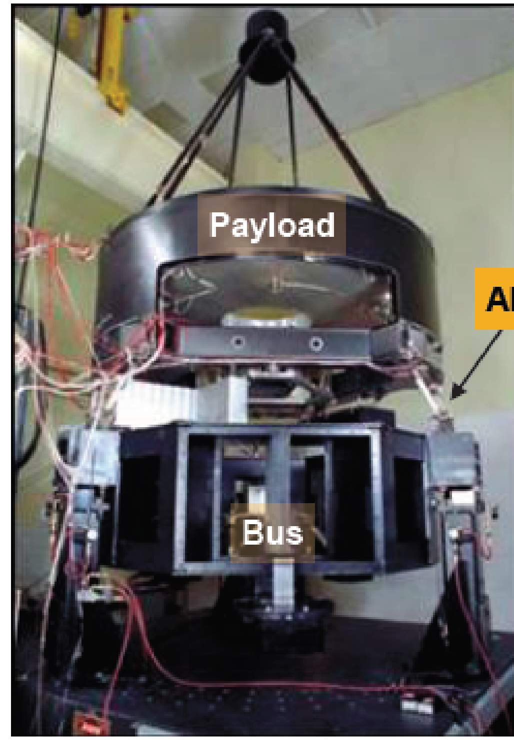
Requirements for EPIC Flight DMs	
Number of DMs	2
Number of Segments	1027
Arrangement	Hex Pack
Control	Piston, Tip, Tilt
Pitch	519 microns
Gaps	<2 microns
Placement precision	+/- 0.5 microns
Range	2.5 microns
Resolution	0.035 nm
Stability / Segm	0.020 nm / 1000 sec
Electronics	16 bits
Coating	Protected Silver
Coating Uniformity	1 % rms
Segment WFE	< 2 nm rms

Active Dynamic Rigid Body Pointing Control

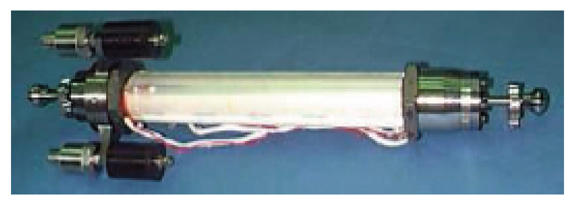
R. Egerman, ITT Space Systems LLC

Active Dynamic Control

- ITT has developed a flight qualified Active Isolation Mount System (AIMS)
  - Includes control electronics
- Technology developed on and demonstrated on 2m class Dynamic Test Unit (DTU)
- ACCESS ASMCS demonstrated a Pointing Control System meeting a 5 nano-radian pointing requirement is attainable



ITT Dynamic Test Unit with AIMS interface between payload and spacecraft simulator



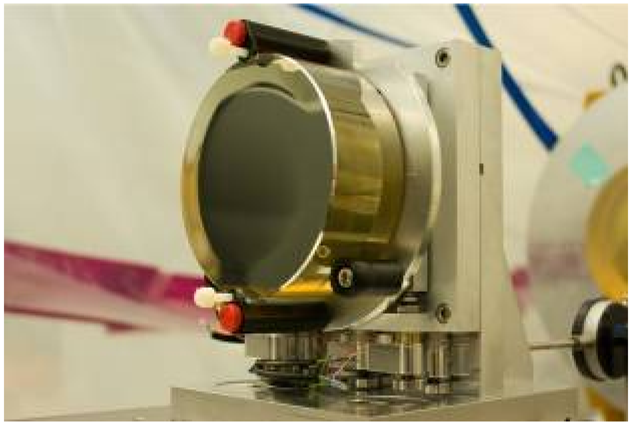
ITT

Precision Optics

PIAA aspheric optics

O. Guyon, Univ of Arizona

- "Hybrid" PIAA + apodizer approach allows the design to be tuned to meet aspheric mirror manufacturing capabilities with little loss in performance
- Metrology and polishing techniques developed in part for extreme-UV lithography now allow manufacturing of high accuracy aspheric surfaces
- PIAA M1 is the most challenging optical element, with strongly curved outer edge. PIAA M2 is considerably easier to polish



2nd Generation PIAA M1 (manufactured by Tinsley)

Two generations of PIAA optics have been manufactured:

•Generation 1 (funded by NASA JPL, manufactured by Axsys): Diamond turned Aluminum (25 nm RMS system WFE)

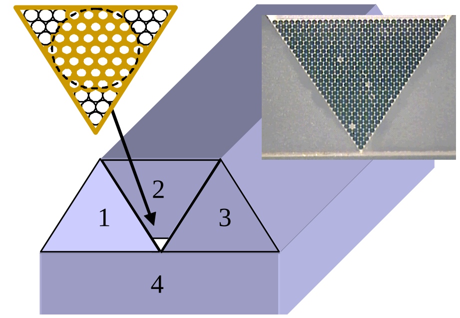
•Generation 2 (funded by NASA Ames, manufactured by Tinsley): Zerodur (10 nm RMS system WFE (filtered to 20 CPA))

• Design of PIAA systems, improvement on manufacturing and laboratory evaluation are advancing in parallel to converge to an optimal PIAA design.

Single Mode Fiber Array assemblies

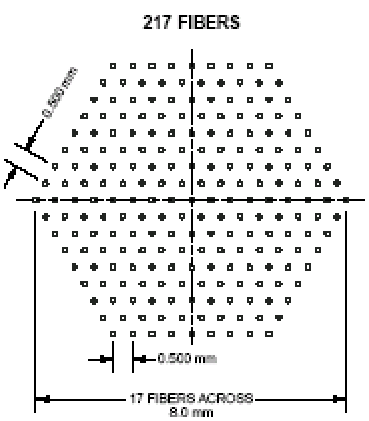
B. M. Levine & M. Shao, JPL

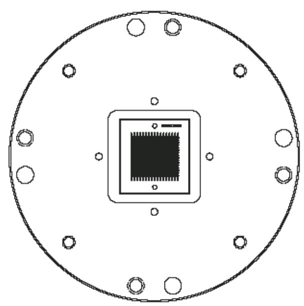
- Development History
  - JPL in-house under TPFC, NASA funding (331 fibers without array)
  - U FL under TPF-C funding, 100 fibers with partial array integration
  - Fiberguide Industries
    - under current procurement contract
    - 217 fibers
    - To be fully integrated with custom lens array
- Future development
  - 1027 fibers fully integrated

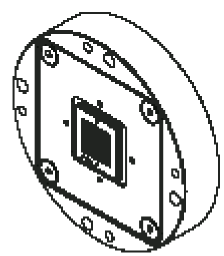


10x10 fiber bundle (6.8 x 2.8 x 63.5 mm)

fiber ends illuminated by a microscope.

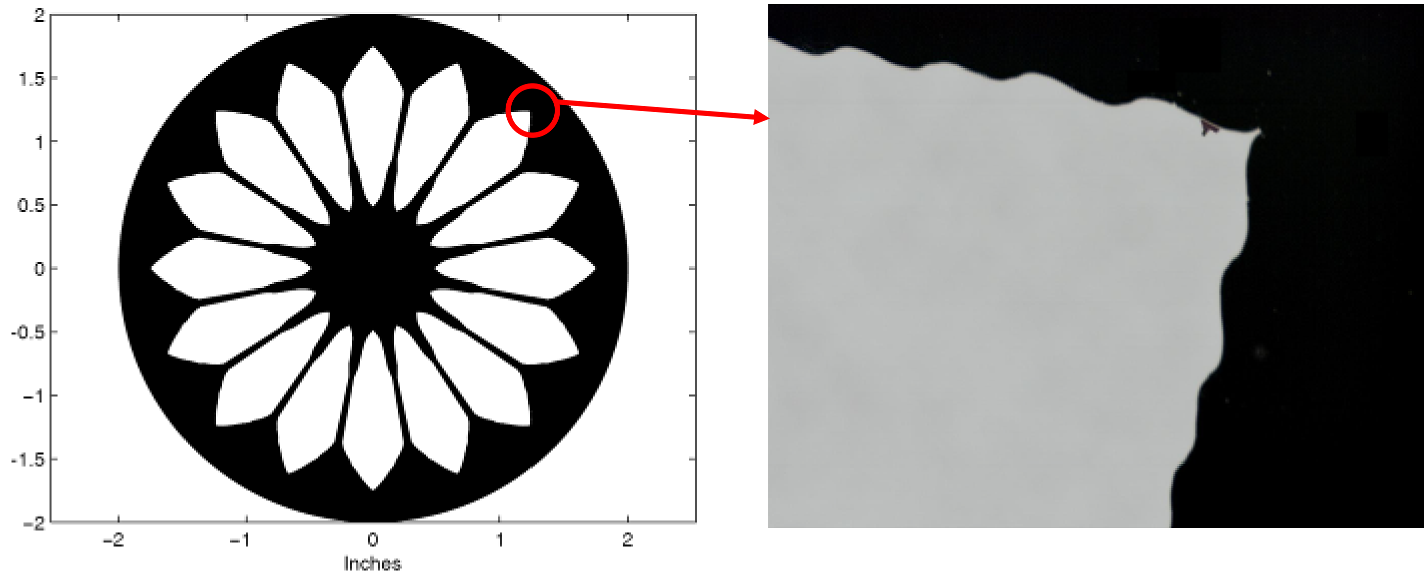


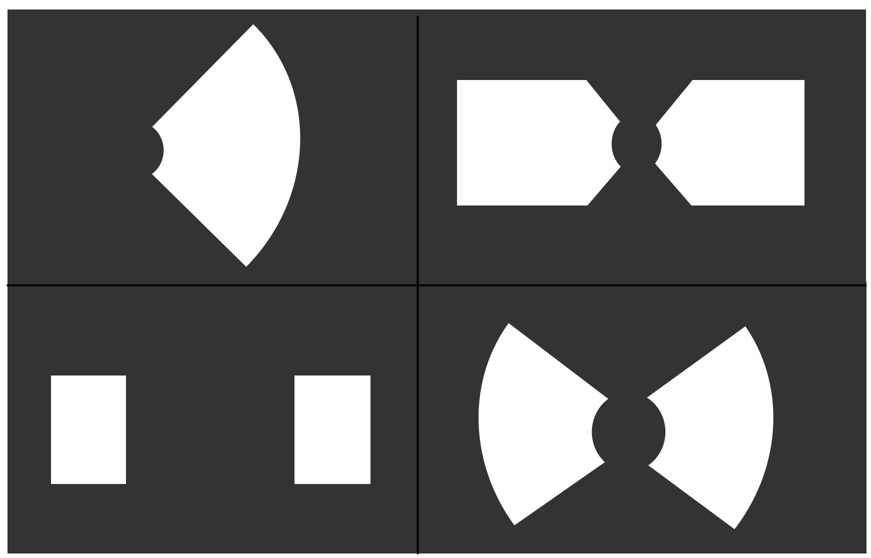




High Precision Lab Scale Free Standing External Occulter and Image Masks Fab'd at JPL Per Princeton Designs

K. Balasubramanian, JPL





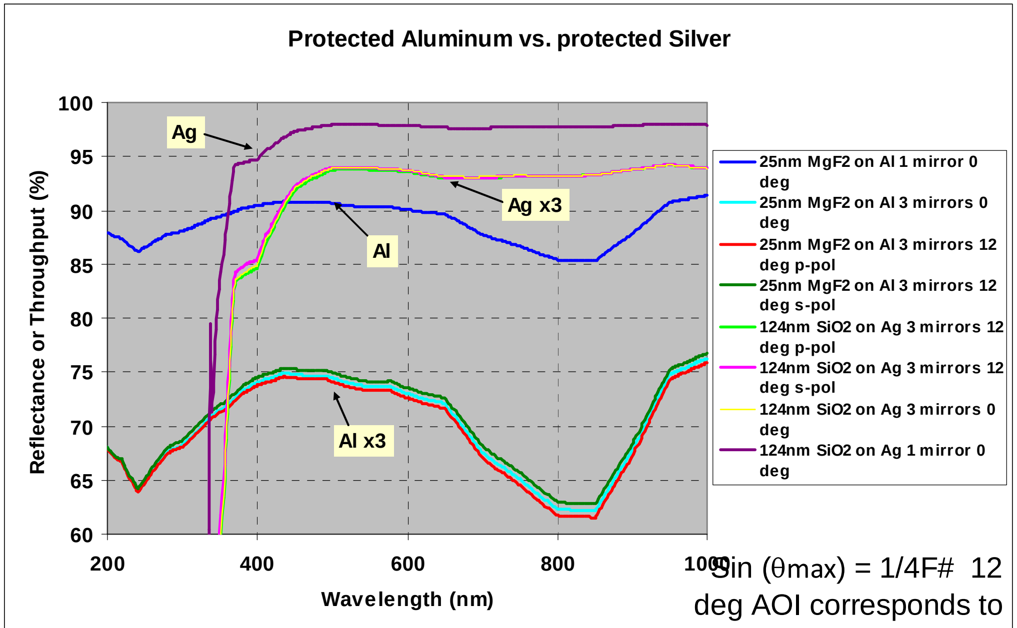
Not to scale

Mirror Coatings – Aluminum or Silver?

K. Balasubramanian, JPL

ExoPlanet Exploration Program

Aluminum	Silver
R ~ 92% Throughput loss	R ~ 98% Better Throughput
UV to IR coverage	UV cut off at 400nm
Undesirable reflectivity dip at ~ 700-900nm	Uniform reflectivity over the full spectrum
Need protection and enhancement	Need protection and UV edge shift
Large Polarization splitting & leakage	Small Polarization splitting & leakage



Sin (θmax) = 1/4F# 12 deg AOI corresponds to F# = 1.2

Theoretically, while a simple 124nm SiO_2 overcoat layer on silver shows good polarization performance without loss of reflectivity, protection and durability may not be adequate.

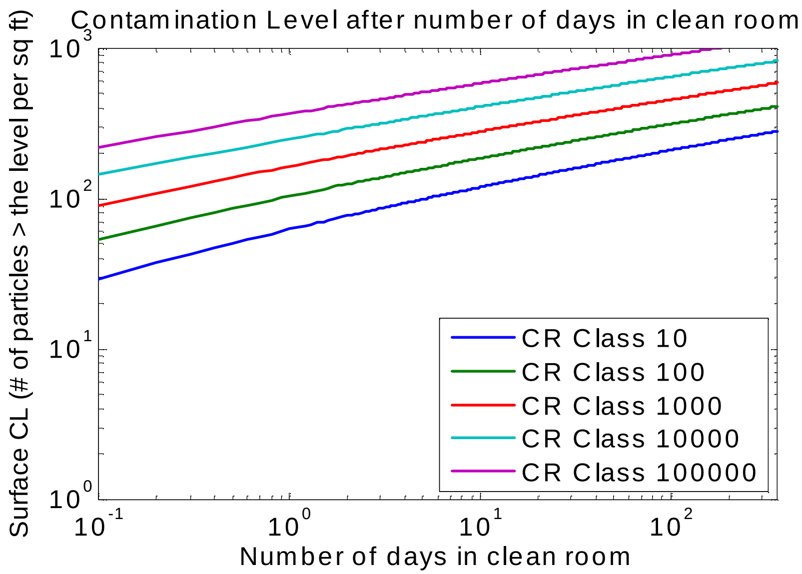
Technology development is progressing.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

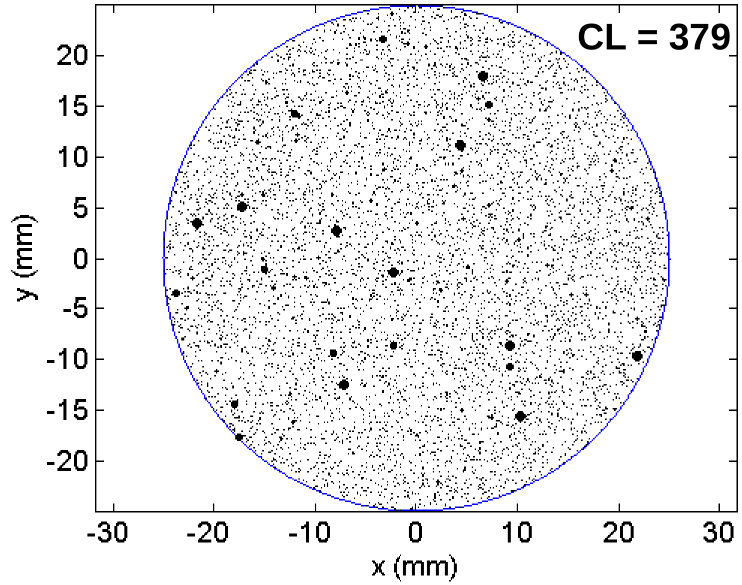
Particulate Contamination on Mirrors and their effect on Coronagraph Performance

K. Balasubramanian, JPL

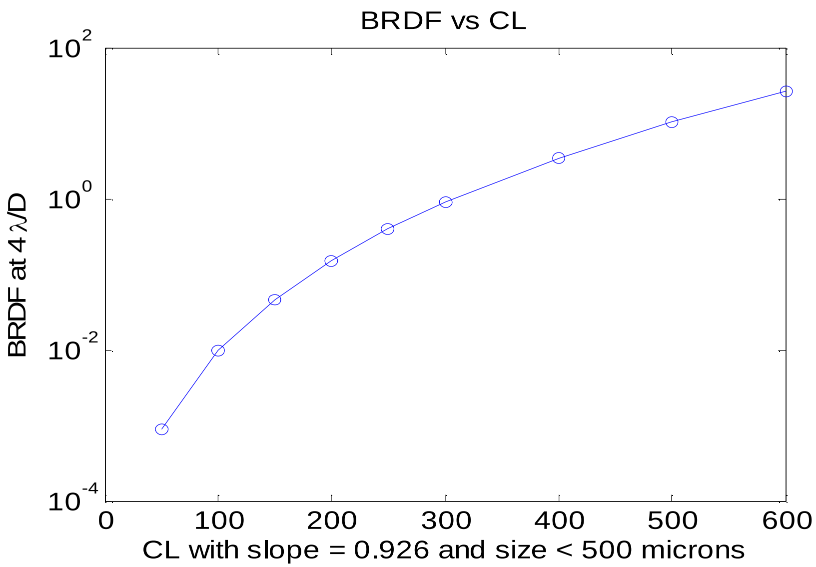
ExoPlanet Exploration Program



A lab mirror imaged and characterized



Particle sizes exaggerated for visualization



Scattered Irradiance Fraction in an Airy spot area

≈ BRDF x π x 10^{-9} (for HCIT @ 785nm)

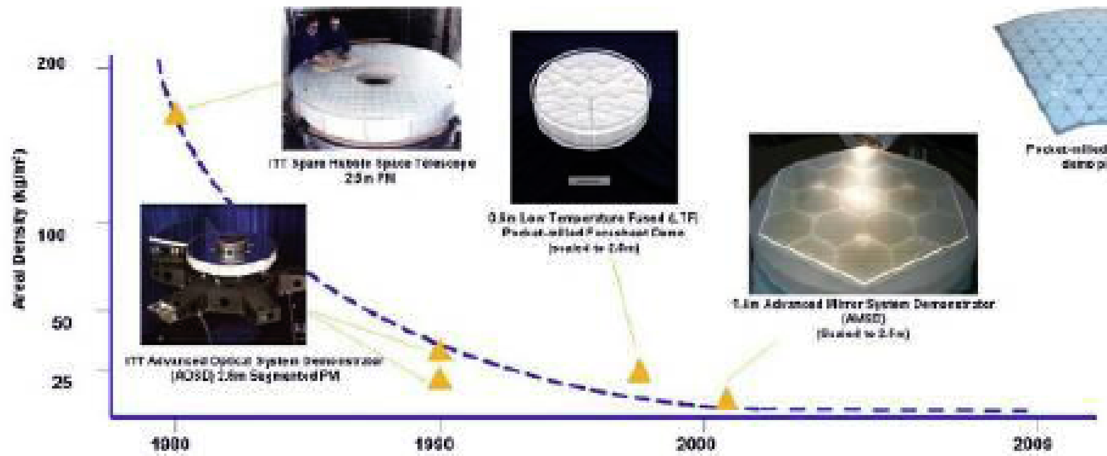
DM's can be employed to compensate for the coherent part of scattered light; work in progress

An OAP from HCIT was characterized to be at CL 300; yet, we achieved a contrast of 5×10^{-10} with DM controls

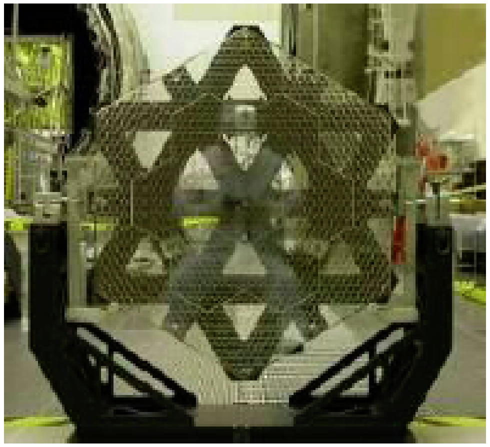
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Primary Mirror SOA Technology

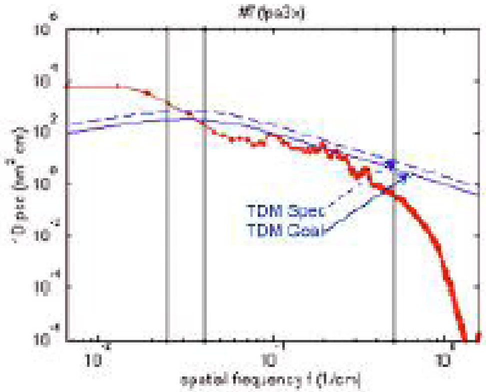
R. Egerman, ITT Space Systems LLC



PM Areal Density, cost, risk and schedule
has been reduced dramatically without sacrificing performance



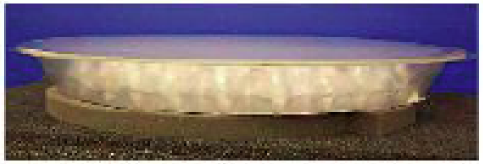
ITT has matured its AMSD ultra-lightweight active mirror bringing it to TRL 6 and demonstrating a reflected WFE of <25 nm-rms



ITT has demonstrated finishing to coronagraphic requirements on 1-2m class on-axis mirrors, off-axis optics in this class do not pose significant challenges

3 layer micro-corrugation facesheet

Layer 4 Macro Corrugation



Finished plano 0.6m mirror blank

ITT has finished a plano 0.6m Corrugated Borosilicate mirror to 380 nm-rms. After one ion figuring run, the error is expected to drop to ~75 nm-rms, and ultimately to ~20nm-rms

ITT

Large Monolithic Mirror (LMM) Technology

R. Egerman, ITT

ExoPlanet Exploration Program

- Current studies are considering monolithic 4m LM PMs with areal densities of ~50kg/m^2
- In comparison to the Hubble Primary mirror which is 2.4m in diameter and has an areal density of ~160 kg/m2, the technical challenge in fabricating and polishing of a LMM to enable diffraction limited performance from 200-400nm upon first glance appears to be a fairly daunting task.
- However, from a technology perspective, **significant advancements have been made since the Hubble PM**
  - Mirror design
  - Mirror fabrication
  - Mirror polishing
- **Significantly reduces technology risk**
  - Essentially turns the task of fabricating a LMM from one of pure technology development to one of a challenging engineering exercise
- **Off-axis LM PMs are more challenging, but not nearly as much as they were 5-10 years ago**

Technology	Benefit	Related Programs
Dynamic Abrasive Water Jet Cutting (AWJ)	Rapid cutting of glass to lightweight mirror cores by up to 98% on a per area basis.	Ikonos, Nextview, AMSD, TDM
LTF* Corning ULE® mirror blanks	100% glass optic with a closed back eliminates mid-spatial frequency errors inherent to FRIT mirrors.	AMSD, SHARPI, AFRL DOT
Segmented AWJ cores	Reduced schedule & risk of breaking full size fragile core.	AMSD, TDM, AFRL DOT
Pocket-milled facesheets	Reduces mirror areal density while maintaining a high local stiffness to minimize gravity release uncertainty.	Demo-Optics
Active laps polishing	Rapid convergence in finishing highly aspheric optics using computer control. Smooth, properly figured aspheric optics.	AMSD. Was to be used on TDM. UofA uses on 8m parts.
The combination of pocket-milling and deep segmented AWJ cores	Enables a 4m optic to be designed that has global and local stiffnesses that are in family with large optics (>1m) that ITT has finished to requirements comparable to internal coronagraph.	Proprietary, THEIA, WFTC
Technology advancement in optic and telescope metrology	With the advent of Laser trackers, more precise theodolites, holograms, advanced interferometers and other novel metrology techniques, the challenges in testing a LMM PM and the integration of it into a telescope are significantly reduced from what they would have been even 5 years ago. Impacts all current and future programs	
The following technologies are not required to make a 4m LMM PM, but their development could reduce mission cost and risk if proven to be viable.		
ULE® Welding	Not required, but could enable a large blank to be built up from smaller pieces. First demonstrated in a proof-of-concept experiment funded under the TPF program office on the Large Monolithic Mirror (LMM) program.	
ULE® Boule Development	Not required, but development of larger boules (diameter and thickness) could reduce the schedule and costs required to produce all of the glass required for a LMM	
ULE® Striae Reduction	Not required, visibly detectable layers called striae are developed as a result of non-uniformities in the distribution titanium oxide molecules which are introduced into ULE® during its manufacturing process. Can make smoothing optic more challenging. Technology to minimize striae alleviates this challenge and could improve performance of system.	
Low Temperature Fusion *(LTF) using a gas Furnace	Not required, but if successful, could reduce cost of PM manufacturing by 10's of $M because a new electric furnace would not need to be procured or qualified. Corning currently has a gas furnace that is >8m in diameter. Note: the solid ground based Subaru and Discovery Channel PMs were fabricated in Corning's large gas furnace.	

ITT

3

Mirror Technology Development Areas

R. Egerman, ITT

Technology Investment Area	Technology Benefits	Missions that could befit from the investment
Faster AWJ cutting at depths >50mm	Reduced cycle time and cost	Systems requiring stiff mirrors ranging in aperture from 0.5m and up
Borosilicate Corrugated Mirror Replication Technology	Rapid fabrication of low areal density passive or active mirrors. Processes can be leveraged to ULE®	Ground and spaced based systems. Space systems operating in the IR.
Flame polishing and stretching of ULE®	Shortens material prep time for corrugated or LTF mirrors	Large aperture segmented systems requiring the thermal stability of ULE®
Increased ULE® Boule Size	Enables blanks for LMMs or larger mirror segments to be fabricated at lower cost and schedule	All programs requiring light-weight ULE® optics with an aperture >1.4m
Reduction of ULE® Striae	Smoother ULE® optics	Primarily exoplanet missions which require a very smooth mirror at all spatial frequencies
Replicated ULE® mirrors	Reduced Cycle Time and Cost	Any large volume ground or space based system
Actuator Technology	Flight qualifies actuators	Large segmented space borne systems.
Zerodur® LTB	A new method for making light-weight closed back mirrors	Space mission requiring a stiff closed back optic with high thermal stability
Actuated SiC Nanolaminate mirrors	Another architecture for IR systems, and a potential for visible and UV systems.	Large space based segmented systems
ITT Active lap technology as a sub-aperture lap	More efficient smoothing of large (>2m) on-and off axis optics	Missions requiring >2m mirrors or mirror segments
ULE® Welding	Another method of fabricating LMMs (≥4m) with potential cost, schedule and risk benefits	Missions such as THEIA, TPF-C, and TPF-NWO
Closed-Back SiC Mirrors	Improved thermo-elastic performance in a SiC mirror	Various
Glass Pocket-Milling Technology	Mature to TRL-6 enabling lighter optics to be fabricated	Various
LTF/LTS in Gas Fired furnace	Eliminates tens of $M in a new electric furnace and its qualification	Missions requiring LMMs

Modeling and Simulation

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Coronagraph Error Budget Tool

L. Marchen & S. Shaklan, JPL

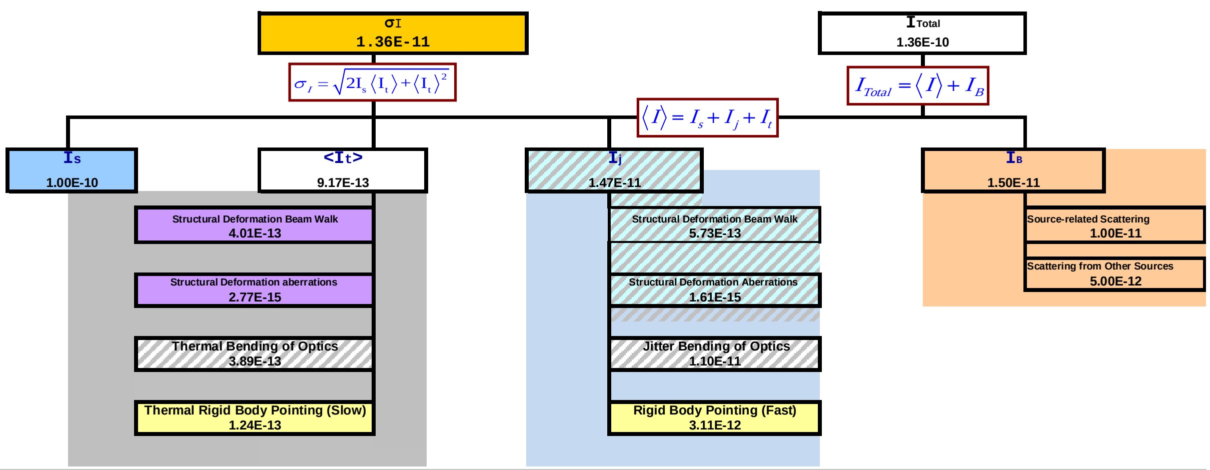
net Exploration Program

- **Purpose**: Create a spreadsheet-based tool that generates a coronagraph error budget with a minimal number of steps.

- **Approach:** There are 5 'pushbutton' steps:
  1. Start with Code V prescription and convert to MACOS.
  2. Compute beamwalk and aberration sensitivity matrices
  3. Read in supplied aberration-to-contrast sensitivity matrix (this is coronagraph specific).
  4. Read files into excel and populate the error budget
  5. Adjust motion /bending allocations as needed..

- **Status:** The tool is built and being tested using an ASMCS optical prescription

Coronagraph Error Tree:



Top Level Errors

		2 λ/D	2.5 λ/D	3 λ/D	4 λ/D	8 λ/D
Final Contrast =	WFE +Background	1.36E-10	1.26E-10	1.26E-10	1.28E-10	1.29E-10
$\sigma_I = \sqrt{2I_s\langle I_t\rangle + \langle I_t\rangle^2}$		1.36E-11	1.14E-11	1.24E-11	1.42E-11	1.73E-11
$\langle I_t\rangle$		9.17E-13	6.45E-13	7.63E-13	1.00E-12	1.48E-12
I_j		1.47E-11	8.11E-13	9.20E-13	1.58E-12	1.83E-12
I_s		1.00E-10	1.00E-10	1.00E-10	1.00E-10	1.00E-10

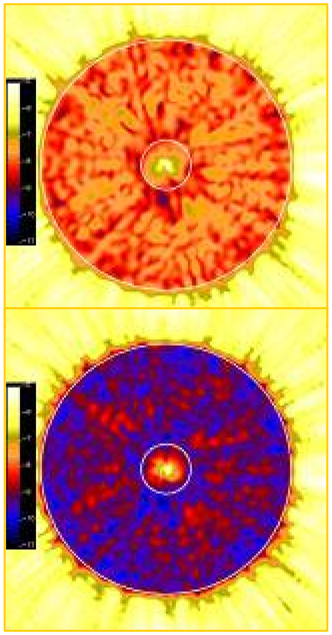
PIAA Modeling

J. Krist, JPL

- End-to-end modeling of PIAA coronagraph with realistic optics and wavefront control
  - Investigate ability to create high contrast fields over broad passband
    - Appears that broadband control is more difficult with PIAA than Lyot coronagraphs (DMs before PIAA)
  - Establish optical surface requirements
    - Optics between PIAA and occulter must be super-polished
- Evaluation of modeling methods (S-Huygens, remapping with Talbot effect, pure remapping) in terms of accuracy and speed

EFC Wavefront Control over 20% Bandpass (500-600 nm)

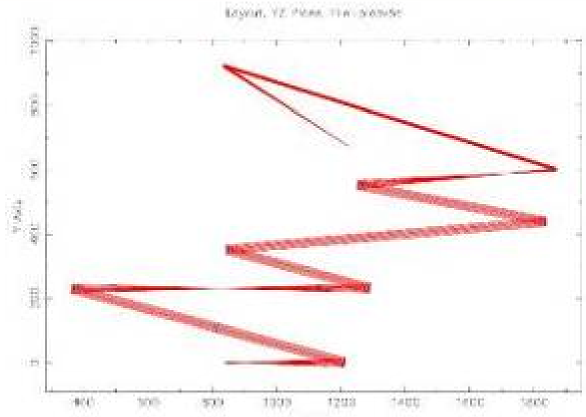
The top map shows the contrast limit when all of the non-primary optics have 1.25 nm RMS surface errors (mean contrast = 1.8×10^{-8}), and on the bottom when the surface errors on just the post-PIAA OAPs and near-focus flats are reduced to 0.25 nm RMS (mean contrast = 8.3×10^{-10}).

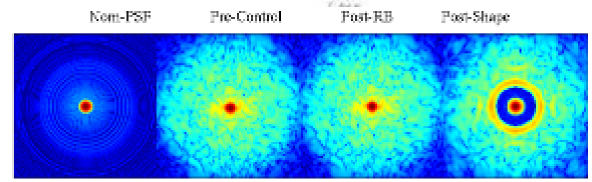


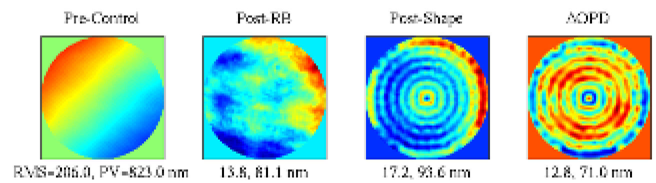
HCIT PIAA Sensitivity Studies

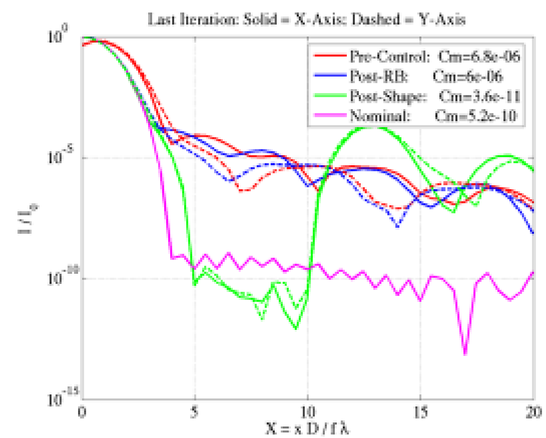
E. Sidick & S. Shaklan, JPL

- **Purpose:** Study the sensitivity of broad-band contrast to alignment, motion, bending, and other perturbations in the PIAA implementation of HCIT.
- **Approach:** Combine a diffraction model of PIAA with a MACOS model of the testbed, and apply the latest EFC algorithm for WFS/C using single and dual DMs.
- **Status:** The model is built and debugging is nearly complete. Initial sensitivity studies are underway.









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External Occulter Performance Modeling

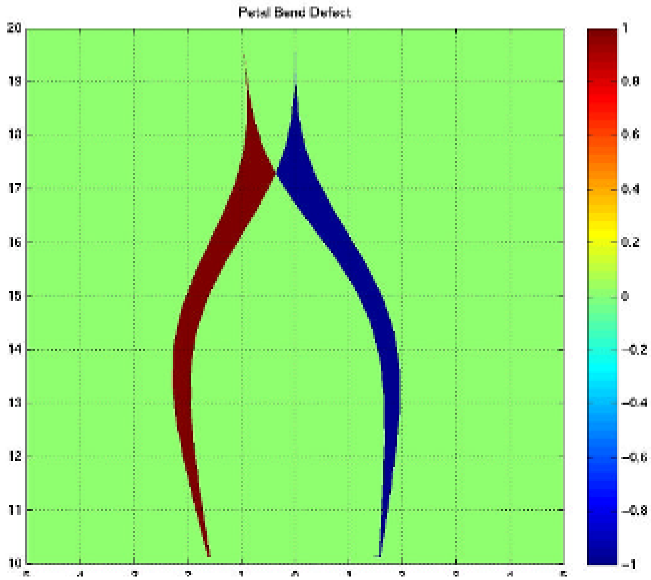
P. Dumont & S. Shaklan, JPL

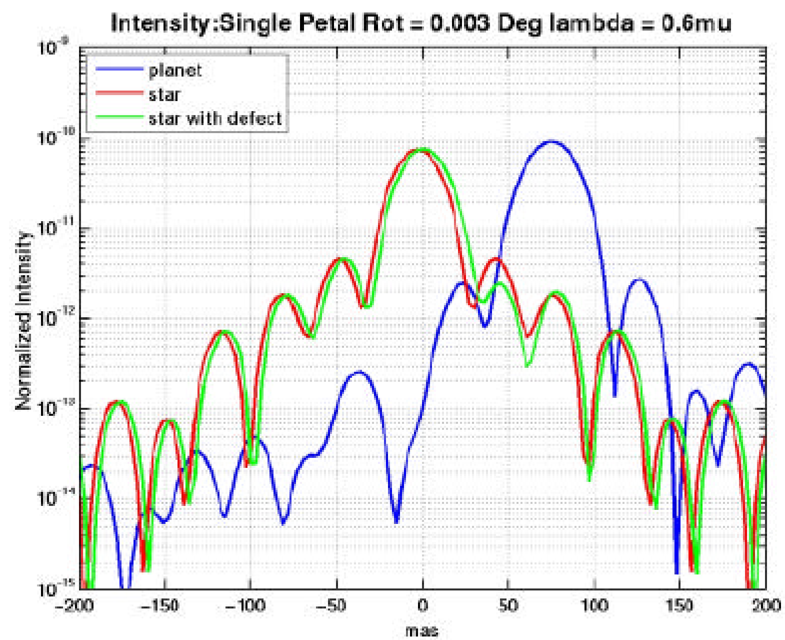
ExoPlanet Exploration Program

- Purpose: Develop the capability to accurately, and efficiently model broad-band occulter performance, for stand-alone and hybrid coronagraph/occulter systems.

- Approach: combine an analytic solution for the occulter field at the telescope with a near-field diffraction model of the optical system.
  - Defects along the occulter petals are modeled as a set of small slits whose fields are combined with the nominal occulter field using Babinet's Principle.
  - Performance is evaluated at the inner working angle in the telescope focal plane.

- *Status*: Coding is completed and some validation vs. analytical solutions and other codes has been done.





Exoplanet Modeling Capabilities at GSFC

R. Lyon, GSFC

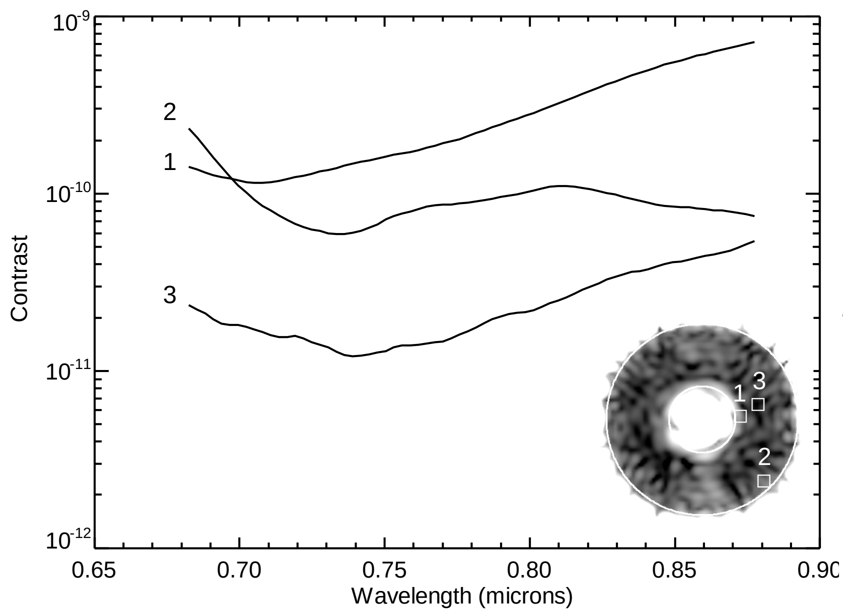
ExoPlanet Exploration Program

- Comprehensive end-to-end model of VNC completed as part of EPIC ASMC study
  - includes all surfaces, raytrace, diffraction, polarization, dispersion, fibers and detectors, etc... (I'll show results from this during EPIC talk)
- Fiber modeling: Propagation within fibers (3D solver) and overlap integral approach for mode overlap (simple)
- Models of external occulters developed
  - Three propagation from occulter to telescope: (1) Fresnel (brute force w/big FFTs), (2) Bessel functions, (3) Edge Line integral
  - Also error models for shape errors and rigid body motions of external occulter
- Vector diffraction: Some capabilities for vector diffraction via rigorous approach (limited by computer power)

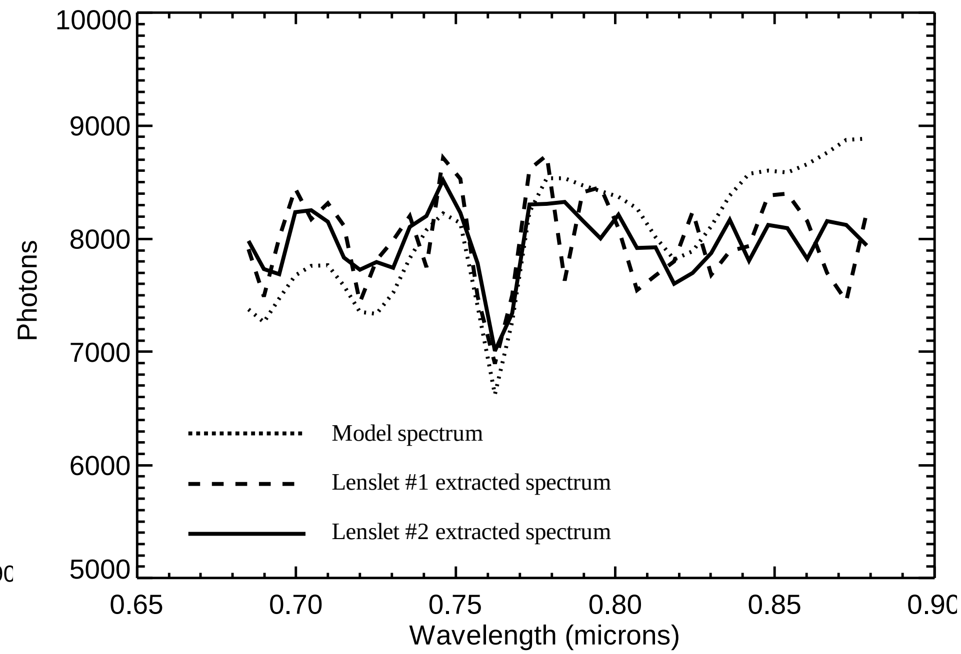
Extraction of Planet Spectra

J. Krist, JPL

- End-to-end model of Lyot coronagraph with aberrations, wavefront control
- Chromaticity of speckles determined
- Planet spectra extracted via roll subtraction, spectral filtering



Spectra of selected background speckles in a wavefront-corrected coronagraphic dark field.



Extracted Earth spectrum from a simulated Coronagraphic dark field.

Cielo: Integrated Modeling of Opto-Thermo-Structures–Controls

G. Moore, M. Chainyk, C. Hoff, JPL

Objectives

- Offer fundamentally integrated analysis for precision observatories, deployable, and other advanced systems
- Enable closed-loop, system-level analysis and design, correlation and optimization

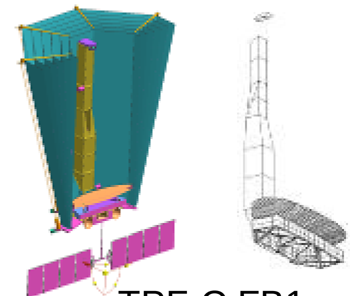
Predict the time dependent wave front error from one model which includes all analysis steps with the feedback loops closed.

Approach

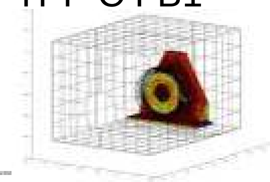
- Develop general purpose finite element based code capable of analyzing integrated models with multi-physics attributes (thermal, structural, optical)
- Matlab based client with GUI connecting to high performance parallel servers
- Native support for Nastran based input file formats for seamless interface to COTS tools

Status

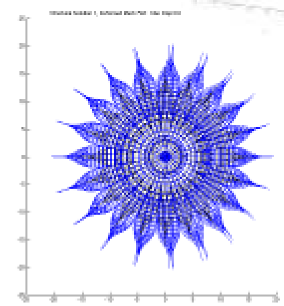
After successfully demonstrating program capability in FY'08 (TOM3 test bed analysis) for precision mK/pm applications, Cielo is being extended to routinely handle models with radiation surfaces numbering in the hundreds of thousands, with structural degrees of freedom numbering in the millions



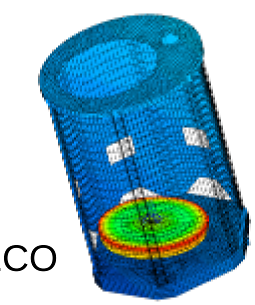
TPF-C FB1



TOM3



THEIA



PECO

Facilities

High Contrast Imaging Testbed - HCIT

Facility

- Vacuum Chamber – L = 7.5′; ø = 6′; P = 1 mTorr Seismically isolated, T-stabilized ~ 10 mK
- Achieved 3×10^{-10} contrast (narrowband)
- Wavefront control with 32x32mm Xinetics Deformable Mirrors w/ 1mm pitch. 64x64mm soon.
- Fiber/Pinhole "Star" Illumination
  - Monochromatic: 635, 785, 809 and 835 nm
  - 2, 10 and 20% BW around 800 nm center
  - Medium and High Power Supercontinuum Sources
- Low-Noise ($5e^-$) CCD Camera, 13 μm Pixels
- Complete Computer Control
- Data Acquisition/Storage
- Safe and Convenient Optical Table Installation/Removal
- Parallel In-Air Preparation and Testing of Modifications to Coronagraphs

Instruments

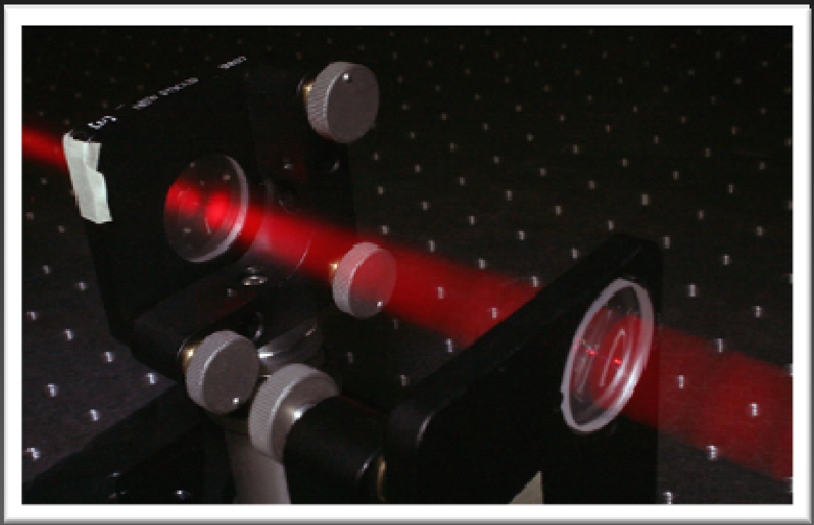
- LYOT Coronagraph – Table #1
  - Band-Limited Occulting Masks
    - e^--beam radiated HEBS Glass
    - Coated Metal and Metal-Hybrid Phase Corrected Masks
  - Shaped-Pupil Masks
  - Vector-Vortex Masks
- *P*hase-*I*nduced-*A*mplitude-*A*podization (PIAA) Coronagraph – Table #2
- Custom-Built Surface Gauge for DM Testing
- Coating Chamber for Occulting Masks
- High-Resolution ZYGO Phase-Shifting Interferometer

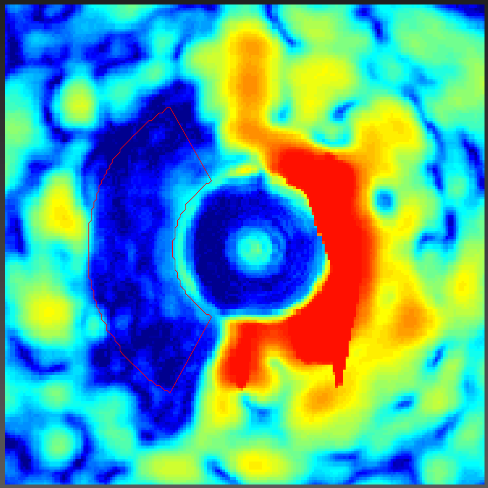
HCIT with Lyot Coronagraph Installed

HCIT with Lyot Coronagraph Installed

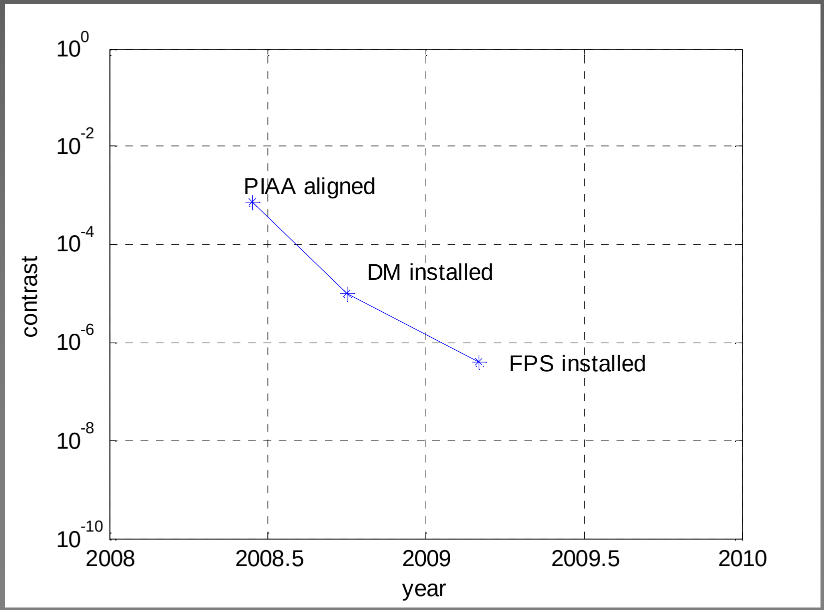
NASA Ames PIAA Coronagraph Experiments

R. Belikov, NASA Ames





4 x 10^{-7} from 2.4 – 5 λ/D



- New testbed, dedicated to PIAA
- Temperature-stabilized air environment
- Flexible and reconfigurable
- Collaboration with HCIT
- Goals
  - study feasibility of MEMS DMs
  - explore architecture trade-offs
  - dichroics and multiple channe
- Contrast of 4 x 10^{-7} demonstrated so far in monochromatic light
- Stability better than 10^{-8}

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ASMCS/JPL Visible Nuller Infrastructure: APEP

P. Lawson & J. Sandhu, JPL

ExoPlanet Exploration Program

Vacuum facility supported

- Optical layout as shown on the right
- Design coordinated with M. Shao & M. Clampin
- Includes DM, pupil and science cameras
- Leverages technology development from TPF-I, Gemini Planet Imager, and SIM

16-Bit DM Electronics for Vacuum

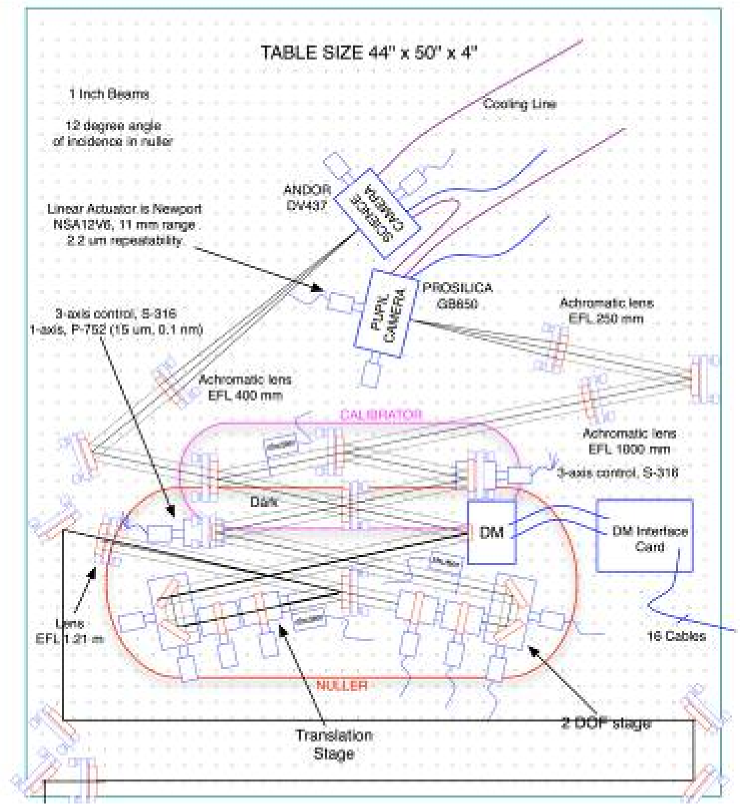
- Minimizes feed-throughs into vacuum tank
- Designed for Boston Micromachines segmented DM
- Conductively cooled electronics and chassis
- Analog boards and chassis now being procured

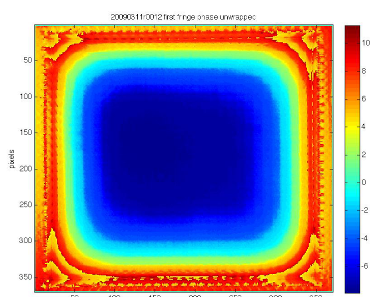
Coherent Fiber Bundle and Lens Array

- Prototype of 217 fibers, with map of fiber positions
- Vitrum to produce custom lens-array, based on map
- Long lead time procurement

Control System Based on RTC

- Initially using a continuous face-sheet DM
- Allows early algorithm development





DM Phase Map

ASMCS Demonstration #1:
Laboratory demonstration of coherent fiber-bundle spatial filter

ASMCS Demonstration #2:
Laboratory vacuum demonstration of broadband visible nulling through fiber bundle

ASMCS Demonstration #3:
Laboratory vacuum demonstration of visible nulling calibration

Visible Nuller Testbeds at NASA GSFC

R. Lyon, GSFC

EPIC has developed two GSFC VNC testbeds and is collaborating with JPL on a 3rd VNC testbed

- Vacuum VNC testbed:
  consists of nulling interferometer with shear/piston control, achromatic phase plates and output ports for both bright and null arms in both pupil and focal planes. We expect to shortly achieve ~10^-9 contrast at TBD IWA in thermal light with > 5% spectral passband. This testbed has been inserted into tank and is fully operational and I'll show results during EPIC talk.
- Null Control Breadboard
  - Purpose: Calibrate DMs, fiber bundle and algorithm development
  - Developed for segmented DM calibration and control algorithm development, consists of a white light Michelson interferometer, interchangeable DMs (IRIS-AO-37 and BMC-61).
  - Three algorithms developed and demonstrated for closed-loop control from pupil plane in white light. Best algorithm has demonstrated wavefront control to < 2 nm rms over 14 hours continuous and < 0.7 nm short terms (few tens of seconds) in closed-loop at 6.7 Hz in air (not vacuum) with no spectral filters on a thermal source. Efforts are continuing to sense and control from focal plane.
  - Coherent fiber bundle (217 fibers) in procurement, expect delivery at GSFC in June 2009, first will be used with BMC-61

Formation Flying Technology Laboratory

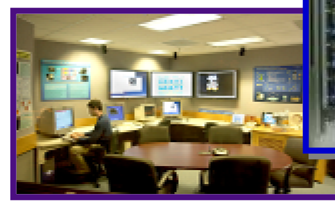
D. Scharf, JPL

ExoPlanet Exploration Program

- The Formation Flying Technology Laboratory (FFTL) is a high-fidelity, system-level formation testbed for end-to-end dynamic 6DOF simulations and demonstrations
  - Distributed real-time simulation environment ***FAST***
    - Flight-like PPC750 single board computers with VxWorks for flight software
    - Each spacecraft simulated on separate dynamics computer
    - Networked via via microsecond-latency LAN and HYDRA middleware
    - Generalization of single-s/c real-time software testbed to multiple s/c
  - Two-robot, flight-like ***Formation Control Testbed (FCT)***
    - 6DOF robots with thrusters, reaction wheels, star tracker, gyros, inter-robot and "ground"-to-robot communication
    - Onboard PPC750s: test software in FAST, migrate directly to robots
    - Highest-fidelity ground validation environment

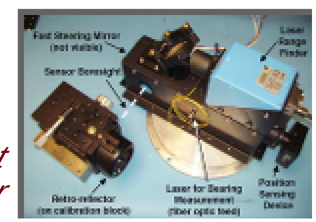
FAST

FFTL Operations Room



- Example External Occulter application: Demonstration of Precision Bearing Control with Attitude and Bearing Sensor Misalignments
  - Pointing telescope+occulter while maintaining lateral alignment *couples formation attitude and formation translation control*
  - Autonomous acquisition of fine bearing sensor and calibration of misalignments at varying sun angles (varying thermal environment) key
    - 1 m lateral alignment at 30,000 km is ~30 nrad req.
  - Demonstrate acquisition/calibration with multi-level sensing in FCT
  - Demonstrate integrated formation pointing and alignment capability

FCT



Inter-Robot Bearing Sensor

Other Test Facilities at GSFC

R. Lyon, GSFC

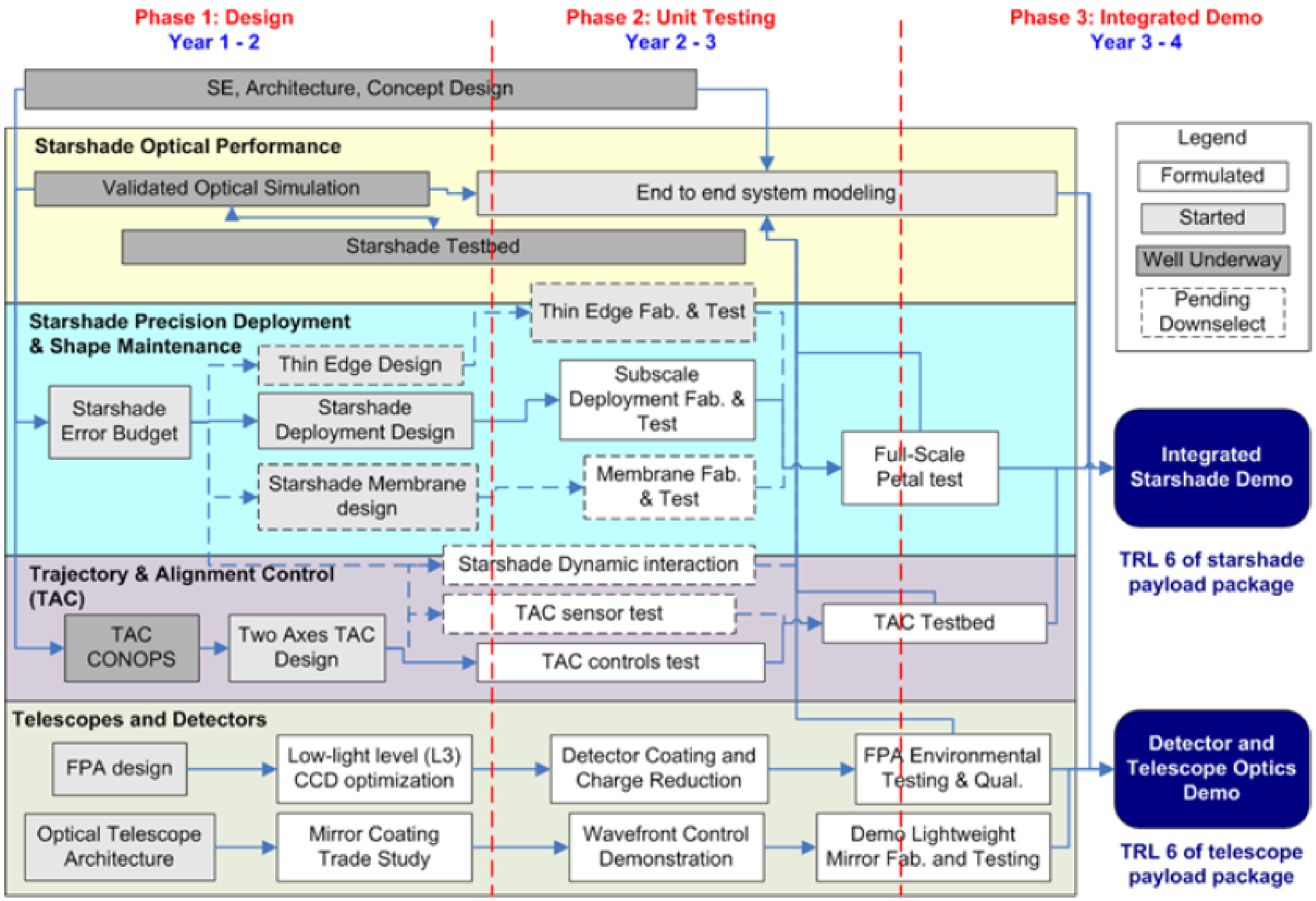
- FAUST (D. Content) scatterometer for measuring edge effects from external occulter materials
- External Occulter Testbed (EOT) under evaluation at GSFC
- Fizeau Interferometry Testbed, closed-loop control with nulling on phase-arrays
- Solar Viewing Interferometry Prototype (SVIP) => precursor for Balloon Exoplanet Nulling Interferometer (BENI)

Other Technologies

NWO Starshade Technology Development Plan

A. Lo, NGST

ExoPlanet Exploration Program



For more details, please see talk "Starshade Technology Development" on April 23rd, 10:50 am

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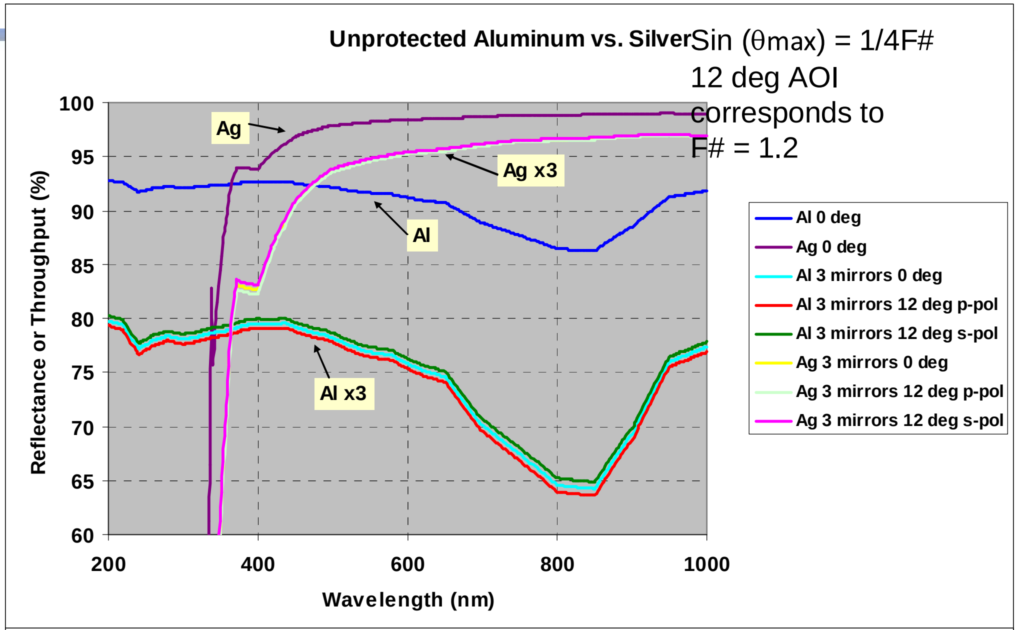
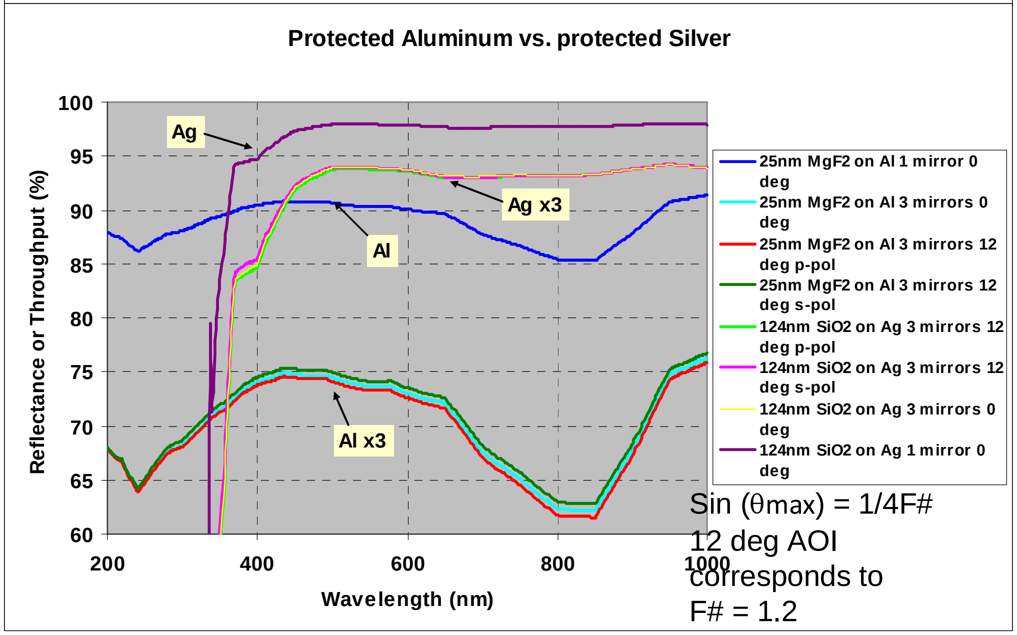
Mirror Coatings – Aluminum or Silver?

K. Balasubramanian, JPL

Aluminum	Silver
R ~ 92% Throughput loss	R ~ 98% Better Throughput
UV to IR coverage	UV cut off at 400nm
Undesirable reflectivity dip at ~ 700-900nm	Uniform reflectivity over the full spectrum
Need protection and enhancement	Need protection and UV edge shift
Large Polarization splitting & leakage	Small Polarization splitting & leakage





Theoretically, while a simple 124nm SiO_2 overcoat layer on silver shows good polarization performance without loss of reflectivity, protection and durability may not be adequate.
Technology development is progressing.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

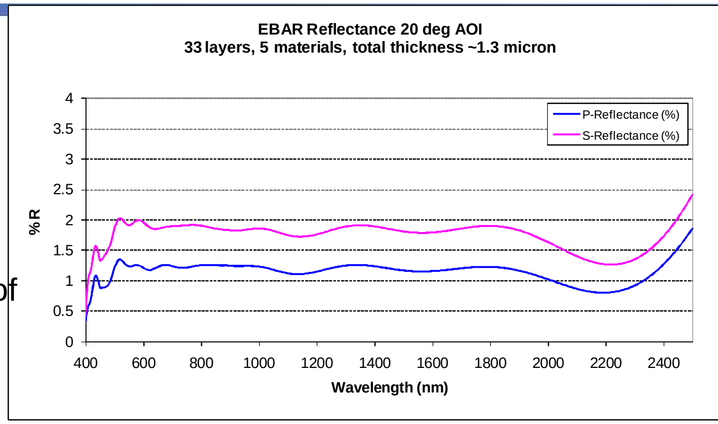
Broadband AR Coatings and Cascaded Dichroic Coatings

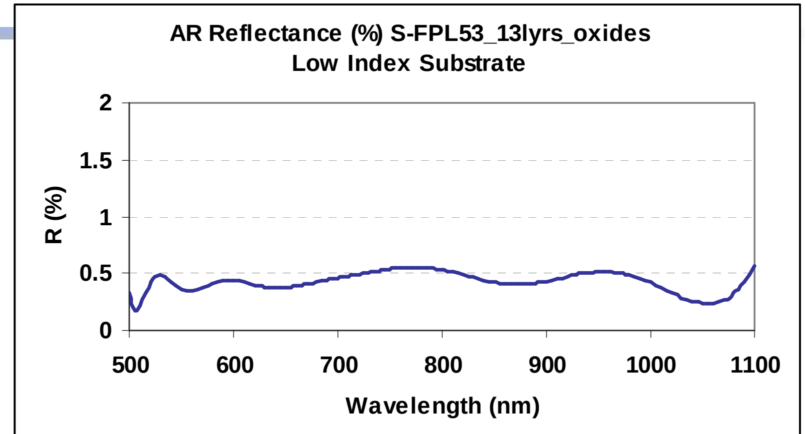
K. Balasubramanian, JPL

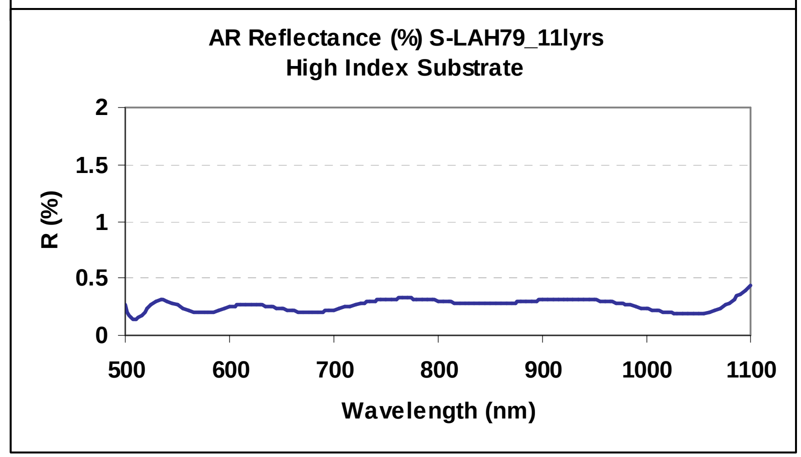
ExoPlanet Exploration Program

BBAR

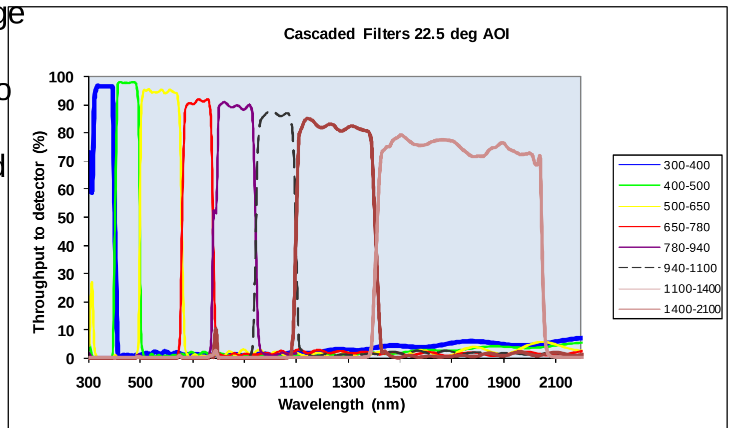
Notes: These theoretical design curves based on assumptions of material properties are subject to potentially large variations in practice due to real material properties and coating processes.







Cascaded Dichroics



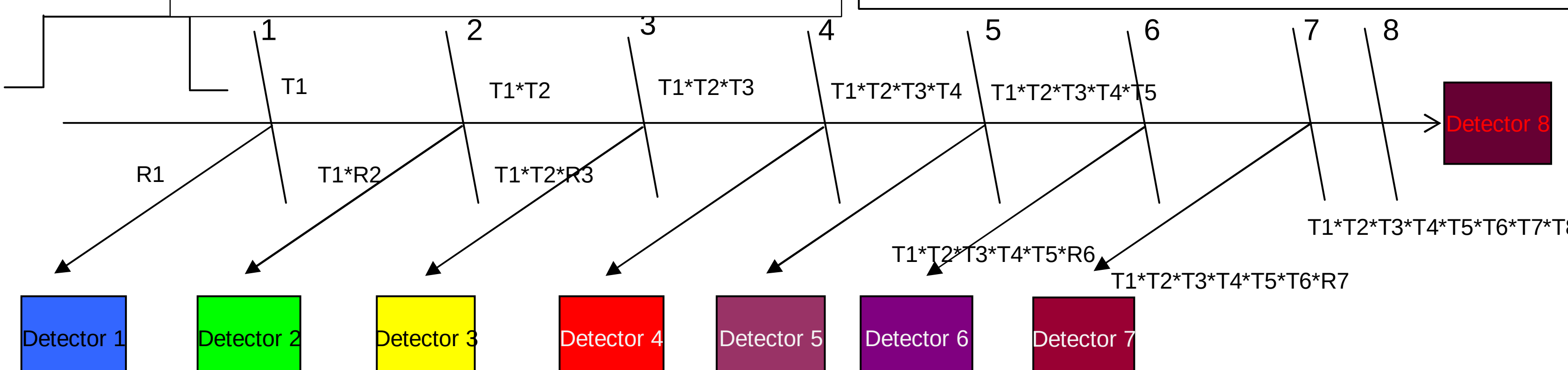


Image Compression (1/2)

R. Egerman, ITT

JPEG 2000 (J2K)

- As space science mission data collection capability continues to grow, the limiting factor will be the ability to communicate the data to the ground
- Future systems are projected to be able to collect pixels at rates orders of magnitude greater than today such as:
  - Star Formation Camera (SFC) at over 3 billion pixels
  - Joint Dark Energy Mission (JDEM) has over 0.5 billion pixels
  - European Space Agency (ESA) Gaia has over 1.0 billion pixels

JPEG 2000 Advantages
- Improved compression efficiency
- 5 – 15 % improvement
- Increased functionality
- Resolution scalability
- Quality scalability
- Region of interest access
- Optimized streaming

Improved compression decreases storage and bandwidth requirements, which reduces cost.

Resolution Scalability enables fast access to multiple resolutions (quick zoom in and out)

Quality Scalability enables pre- and post-compression tradeoff and selection of data rate and quality

Region-of-Interest access enables fast access to any region, at any quality, and resolution.

JPIP enables the intelligent access to the scalability features through TCP/IP (client/server –web access)

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Image Compression (2/2)

R. Egerman, ITT

JPEG 2000

J2K changes image handling paradigm significantly

- Enables more efficient use of data downlink
- Flexible architecture
- Different missions could benefit significantly, depending on requirements

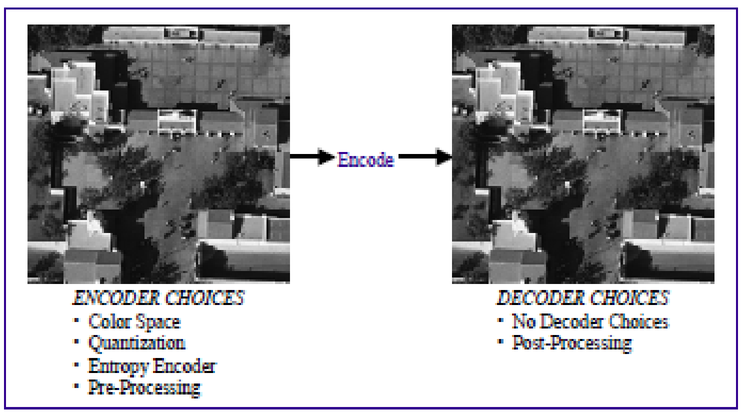

Figure 1: Current compression paradigm

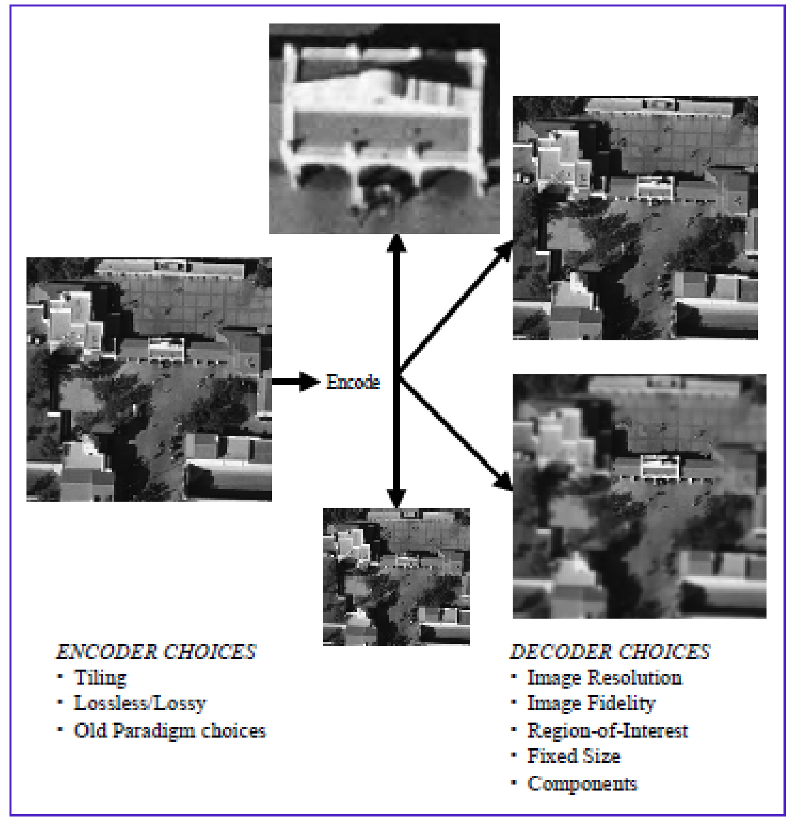

Figure 2: New compression paradigm

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